Frank R. Spellman

Handbook of Water and Wastewater Treatment Plant Operations

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Preface

> Water does not divide; it connects. With simplicity it links all aspects of our existence.
>
> **David Rothenberg and Marta Ulvaenus**

In *Handbook of Water and Wastewater Treatment Plant Operations*, the intent of the author is twofold. The first intent is to consolidate the information and experience in waterworks and wastewater treatment plant operations that have evolved as a result of technological advances in the field, and as a result of the concepts and policies promulgated by the environmental laws and the subsequent guidelines. The second intent is to discuss step-by-step procedures for the correct and efficient operation of water and wastewater treatment systems. Tertiary to this twofold intent is the proper preparation of operators to qualify for state licensure and certification examinations.

With the impetus given to water quality improvement through the Municipal Construction Grants Program, the United States has undertaken an unprecedented building program for new and improved water and wastewater treatment systems. To date, much emphasis has been placed on training engineers to plan, design, and construct treatment facilities. At present, many programs in various engineering disciplines at many universities offer courses in water and wastewater treatment plant design and operation.

This text is not about the planning, designing, or construction of water and wastewater treatment facilities. While these tasks are paramount to conception and construction of needed facilities and needed infrastructure, many excellent texts are available that cover these important areas. This text is not about engineering at all. Instead, it is about operations and is designed for the operator. We often forget the old axiom: someone must build it, but once built, someone must operate it. It is the operation of "it" that concerns us here.

Several excellent texts have been written on water and wastewater treatment plant operations. Thus, the logical question is, why a new text covering a well-trodden road?

The compound answer is a text that is comprehensive in scope, current, and deals with real world problems involved with plant operations is needed. The simple answer is that after September 11, things have changed.

Many of these changes were apparent before September 11; at the same time, many of our present needs were not so apparent. Consider, for example, the need for plants to become more efficient in operation and more economical in practice. This is not new, but it now takes on added importance because of the threat of privatization. We cover privatization and the benchmarking process in this text. On the other hand, how many of us thought security was a big deal prior to September 11? Some of us did, while some of us did not give it any thought at all. Today, things are different; we must adjust or fall behind. In the present climate, falling behind on the security of our potable water supplies is not an option. We must aggressively protect our precious water sources and those ancillaries that are critical to maintaining and protecting water quality. We cover plant security concerns in this text.

There are other current issues. For example, arsenic in drinking water received a lot of coverage in the press recently. We all know that arsenic is a deadly poison, depending on dose, of course. Headlines stating that arsenic has been found in certain municipal drinking water supplies are a red flag issue to many people. But is it really an issue? We cover arsenic in drinking water in this text.

Another red flag issue that has received some press and the attention of regulators is the presence of pathogenic protozoans, such as *Giardia* and *Cryptosporidium*, in drinking water supplies. We cover both of these protozoans in this text.

In wastewater treatment (as well as water treatment), a lot of attention has been focused on disinfection by-products in water effluents outfalled into receiving water bodies. We cover disinfection by-products in this text.

Water and wastewater treatment is about mitigating the problems mentioned above. However, treatment operations are about much more. To handle today's problems, water and wastewater treatment system operators must be generalists. Herein lies the problem. Many of the texts presently available for water and wastewater operator use are limited in scope and narrowly focused in content. Most of these texts take a bare bones approach to presentation. That is, the basics of each unit process are usually adequately covered, but this is the extent of the coverage.

At present, available texts either ignore, avoid, or pay cursory attention to such important areas as the multiple-barrier concept, maintaining infrastructure, benchmarking, plant security, operator roles, water hydraulics, microbiology, water ecology, basic electrical principles, pumping, conveyance, flow measurement, basic water chemistry, water quality issues, biomonitoring, sampling and testing, water sources, and watershed protection. All of these important topics are thoroughly discussed in *Handbook of Water and Wastewater Treatment Plant Operations*.

Though directed at water and wastewater operators, this book will serve the needs of students; teachers; con-

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sulting engineers; and technical personnel in city, state, and federal organizations who must review operations and operating procedures. In order to maximize the usefulness of the material contained in the test, it has been presented in plain English in a simplified and concise format. Many tables have been developed, using a variety of sources.

To assure correlation to modern practice and design, illustrative problems are presented in terms of commonly used operational parameters.

Each chapter ends with a chapter review test to help evaluate mastery of the concepts presented. Before going on to the next chapter, take the review test, compare your answers to the key provided in Appendix A, and review the pertinent information for any problems you missed. If you miss many items, review the whole chapter.

The indented notes displayed in various locations throughout this text indicate or emphasize important points to study carefully.

This text is accessible to those who have no experience with water and wastewater operations. If you work through the text systematically, you can acquire an understanding of and skill in water and wastewater operations. This will add a critical component to your professional knowledge.

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Norfolk, VA

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PART I

Water and Wastewater Operations: An Overview

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1 Problems Facing Water and Wastewater Treatment Operations

What is of all things most yielding,
Can overcome that which is most hard,
Being substanceless, it can enter in
even where there is no crevice.
That is how I know the value
of action which is actionless.

Lao Tzu, 5th Century B.C.

1.1 INTRODUCTION

Although not often thought of as a commodity (or, for that matter, not thought about at all), water is a commodity — a very valuable commodity. In this text, it is our position that with the passage of time, potable water will become even more valuable. Moreover, with the passage of even more time, potable water will be even more valuable than we might imagine. It may be possibly comparable in pricing, gallon for gallon, to what we pay for gasoline, or even more.

Earth was originally allotted a finite amount of water — we have no more or no less than that original allotment today. It logically follows that, in order to sustain life as we know it, we must do everything we can to preserve and protect our water supply. We also must purify and reuse the water we presently waste (i.e., wastewater).

1.2 THE PARADIGM SHIFT

Historically, the purpose of water supply systems has been to provide pleasant drinking water that is free of disease organisms and toxic substances. In addition, the purpose of wastewater treatment has been to protect the health and well being of our communities. Water and wastewater treatment operations have accomplished this goal by (1) prevention of disease and nuisance conditions; (2) avoidance of contamination of water supplies and navigable waters; (3) maintenance of clean water for survival of fish, bathing, and recreation; and (4) generally conservation of water quality for future use.

The purpose of water supply systems and wastewater treatment processes has not changed. However, primarily because of new regulations the paradigm has shifted. These include:

1. Protection against protozoan and virus contamination
2. Implementation of the multiple barrier approach to microbial control
3. New requirements of the Ground Water Disinfection Rule, the Total Coliform Rule and Distribution System, and the Lead and Copper Rule
4. Regulations for trihalomethanes and disinfection by-products (DBPs)

We discuss this important shift momentarily but first it is important to abide by Voltaire's advice: that is, "If you wish to converse with me, please define your terms."

For those not familiar with the term paradigm, it can be defined in the following ways. A paradigm is the consensus of the scientific community — "concrete problem solutions that the profession has come to accept."[1] Thomas Kuhn coined the term paradigm. He outlined it in terms of the scientific process. He felt that "one sense of paradigm, is global, embracing all the shared commitments of a scientific group; the other isolates a particularly important sort of commitment and is thus a subset of the first."[1] The concept of paradigm has two general levels. The first is the encompassing whole, the summation of parts. It consists of the theories, laws, rules, models, concepts, and definitions that go into a generally accepted fundamental theory of science. Such a paradigm is *global* in character. The other level of paradigm is that it can also be just one of these laws, theories, models, etc. that combine to formulate a global paradigm. These have the property of being *local*. For instance, Galileo's theory that the earth rotated around the sun became a paradigm in itself, namely a generally accepted law in astronomy. Yet, on the other hand, his theory combined with other local paradigms in areas such as religion and politics to transform culture. A paradigm can also be defined as a pattern or point of view that determines what is seen as reality.

We use the latter definition in this text.

A *paradigm shift* is defined as a major change in the way things are thought about, especially scientifically. Once a problem can no longer be solved in the existing paradigm, new laws and theories emerge and form a new paradigm, overthrowing the old if it is accepted. Paradigm shifts are the "occasional, discontinuous, revolutionary changes in tacitly shared points of view and preconceptions."[2] Simply,

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a paradigm shift represents "a profound change in the thoughts, perceptions, and values that form a particular vision of reality."[3] For our purposes, we use the term paradigm shift to mean a change in the way things are understood and done.

1.2.1 A Change in the Way Things are Understood and Done

In water supply systems, the historical focus, or traditional approach, has been to control turbidity, iron and manganese, taste and odor, color, and coliforms. New regulations provided new focus, and thus a paradigm shift. Today the traditional approach is no longer sufficient. Providing acceptable water has become more sophisticated and costly.

In order to meet the requirements of the new paradigm, a systems approach must be employed. In the systems approach, all components are interrelated. What affects one impacts others. The focus has shifted to multiple requirements (i.e., new regulations require the process to be modified or the plant upgraded).

To illustrate the paradigm shift in the operation of water supply systems, let us look back on the traditional approach of disinfection. Disinfection was used in water to destroy harmful organisms. It is still used in water to destroy harmful organisms, but is now only one part of the *multiple-barrier approach*. Moreover, disinfection has traditionally been used to treat for coliforms only. Currently, because of the paradigm shift, disinfection now (and in the future) is used against coliforms, *Legionella*, *Giardia*, *Cryptosporidium*, and others. Another example of the traditional vs. current practices is seen in the traditional approach to particulate removal in water to lessen turbidity and improve aesthetics. Current practice is still to decrease turbidity to improve aesthetics, but now microbial removal plus disinfection is practical.

Another significant factor that contributed to the paradigm shift in water supply systems was the introduction of the Surface Water Treatment Rule (SWTR) in 1989. SWTR requires water treatment plants to achieve 99.9% (3 log) removal activation/inactivation of Giardia and 99.99% (4 log) removal/inactivation of viruses. SWTR applies to all surface waters and ground waters under direct influence.

1.3 MULTIPLE-BARRIER CONCEPT

On August 6, 1996, during the Safe Drinking Water Act (SDWA) Reauthorization signing ceremony, President Bill Clinton stated, "A fundamental promise we must make to our people is that the food they eat and the water they drink are safe." No rational person could doubt the importance of the promise made in this statement.

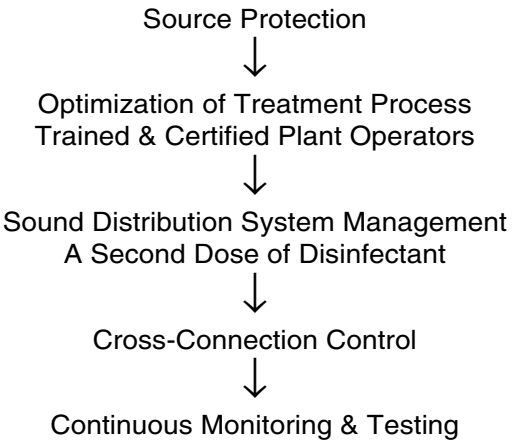

FIGURE 1.1 Multiple-barrier approach.

SDWA, passed in 1974, amended in 1986, and reauthorized in 1996, gives the U.S. Environmental Protection Agency (EPA) the authority to set drinking water standards. This document is important for many reasons, but is even more important because it describes how the EPA establishes these standards.

Drinking water standards are regulations that EPA sets to control the level of contaminants in the nation's drinking water. These standards are part of SDWA's multiple-barrier approach to drinking water protection (see Figure 1.1).

As shown in Figure 1.1, the multiple barrier approach includes the following elements:

1. Assessing and protecting drinking water sources — This means doing everything possible to prevent microbes and other contaminants from entering water supplies. Minimizing human and animal activity around our watersheds is one part of this barrier.
2. Optimizing treatment processes — This provides a second barrier and usually means filtering and disinfecting the water. It also means making sure that the people who are responsible for our water are properly trained and certified and knowledgeable of the public health issues involved.
3. Ensuring the integrity of distribution systems — This consists of maintaining the quality of water as it moves through the system on its way to the customer's tap.
4. Effecting correct cross-connection control procedures — This is a critical fourth element in the barrier approach. It is critical because the greatest potential hazard in water distribution systems is associated with cross-connections to nonpotable waters. There are many connections between potable and nonpotable systems — every drain in a hospital constitutes such a

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connection, but cross-connections are those through which backflow can occur.[4]

5. Continuous monitoring and testing of the water before it reaches the tap — Monitoring water quality is a critical element in the barrier approach. It should include having specific procedures to follow should potable water ever fail to meet quality standards.

With the involvement of EPA, local governments, drinking water utilities, and citizens, these multiple barriers ensure that the tap water in the U.S. and territories is safe to drink. Simply, in the multiple-barrier concept, we employ a holistic approach to water management that begins at the source and continues with treatment, through disinfection and distribution.

1.3.1 Multiple-Barrier Approach: Wastewater Operations

Not shown in Figure 1.1 is the fate of the used water. What happens to the wastewater produced? Wastewater is treated via the multiple-barrier treatment train, which is the combination of unit processes used in the system. The primary mission of the wastewater treatment plant (and the operator/practitioner) is to treat the wastestream to a level of purity acceptable to return it to the environment or for immediate reuse (i.e., reuse in such applications as irrigation of golf courses, etc.).

Water and wastewater operators maintain a continuous urban water cycle on a daily basis. B.D. Jones sums up this point as follows:

> Delivering services is the primary function of municipal government. It occupies the vast bulk of the time and effort of most city employees, is the source of most contacts that citizens have with local governments, occasionally becomes the subject of heated controversy, and is often surrounded by myth and misinformation. Yet, service delivery remains the "hidden function" of local government.[5]

In *Handbook of Water and Wastewater Treatment Plant Operations*, we focus on sanitary (or environmental) services (excluding solid-waste disposal) — water and wastewater treatment — because they have been and remain indispensable for the functioning and growth of cities. Next to air, water is the most important life-sustaining product on earth. Yet it is its service delivery (and all that it entails) that remains a "hidden function" of local government.[5] This hidden function is what this text is all about. We present our discussion in a completely new and unique dual manner — in what we call the new paradigm shift in water management and in the concept of the multiple barrier approach. Essentially, the *Handbook* takes the hidden part out of services delivered by water and wastewater professionals.

Water service professionals provide water for typical urban domestic and commercial uses, eliminate wastes, protect the public health and safety, and help control many forms of pollution. Wastewater service professionals treat the urban wastestream to remove pollutants before discharging the effluent into the environment. Water and wastewater treatment services are the urban circulatory system.[6] In addition, like the human circulatory system, the urban circulatory system is less than effective if flow is not maintained.

Maintaining flow is what water and wastewater operations is all about. This seems easy enough; water has been flowing literally for eons. However, this is not to say that water and wastewater operations are not without problems and/or challenges. The dawn of the 21st century brought with it, for many of us, aspirations of good things ahead in the constant struggle to provide quality food and water for humanity. However, the only way in which we can hope to accomplish this is to stay on the cutting edge of technology and to face all challenges head on. Some of these other challenges are addressed in the following sections.

1.4 MANAGEMENT PROBLEMS FACING WATER AND WASTEWATER OPERATIONS

Problems come and go, shifting from century to century, decade to decade, year to year, and site to site. They range from the problems caused by natural forces (storms, earthquakes, fires, floods, and droughts) to those caused by social forces, currently including terrorism.

In general, five areas are of concern to many water and wastewater management personnel.

1. Complying with regulations and coping with new and changing regulations
2. Maintaining infrastructure
3. Privatization and/or reengineering
4. Benchmarking
5. Upgrading security

1.4.1 Compliance with New, Changing, and Existing Regulations[7]

Adapting the workforce to the challenges of meeting changing regulations and standards for both water and wastewater treatment is a major concern. As mentioned, drinking water standards are regulations that EPA sets to control the level of contaminants in the nation's drinking water. Again, these standards are part of SDWA's multiple-barrier approach to drinking water protection.

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There are two categories of drinking water standards:

1. A National Primary Drinking Water Regulation (primary standard) — This is a legally enforceable standard that applies to public water systems. Primary standards protect drinking water quality by limiting the levels of specific contaminants that can adversely affect public health and are known or anticipated to occur in water. They take the form of Maximum Contaminant Levels or Treatment Techniques.
2. A National Secondary Drinking Water Regulation (secondary standard) — This is a nonenforceable guideline regarding contaminants that may cause cosmetic effects (e.g., skin or tooth discoloration) or aesthetic effects (e.g., taste, odor, or color) in drinking water. USEPA recommends secondary standards to water systems, but does not require systems to comply. However, states may choose to adopt them as enforceable standards. This information focuses on national primary standards.

Drinking water standards apply to public water systems that provide water for human consumption through at least 15 service connections or regularly serve at least 25 individuals. Public water systems include municipal water companies, homeowner associations, schools, businesses, campgrounds and shopping malls.

More recent requirements, including the Clean Water Act Amendments that went into effect in February 2001, require water treatment plants to meet tougher standards. They have presented new problems for treatment facilities to deal with and have offered some possible solutions to the problems of meeting the new standards. These regulations provide for communities to upgrade existing treatment systems, replacing aging and outdated infrastructure with new process systems. Their purpose is to ensure that facilities are able to filter out higher levels of impurities from drinking water, reducing the health risk from bacteria, protozoa, and viruses, and that they are able to decrease levels of turbidity and reduce concentrations of chlorine by-products in drinking water.

In regards to wastewater collection and treatment, the National Pollution Discharge Elimination System program established by the Clean Water Act, issues permits that control wastewater treatment plant discharges. Meeting permit is always a concern for wastewater treatment managers because the effluent discharged into water bodies affects those downstream of the release point. Individual point source dischargers must use the best available technology to control the levels of pollution in the effluent they discharge into streams. As systems age, and best available technology changes, meeting permit with existing equipment and unit processes becomes increasingly difficult.

1.4.2 Maintaining Infrastructure

During the 1950s and 1960s, the U.S. government encouraged the prevention of pollution by providing funds for the construction of municipal wastewater treatment plants, water-pollution research, and technical training and assistance. New processes were developed to treat sewage, analyze wastewater, and evaluate the effects of pollution on the environment. In spite of these efforts, expanding population and industrial and economic growth caused the pollution and health difficulties to increase.

In response to the need to make a coordinated effort to protect the environment, the National Environmental Policy Act was signed into law on January 1, 1970. In December of that year, a new independent body — EPA — was created to bring under one roof all of the pollution-control programs related to air, water, and solid wastes. In 1972, the Water Pollution Control Act Amendments expanded the role of the federal government in water pollution control and significantly increased federal funding for construction of wastewater treatment plants.

Many of the wastewater treatment plants in operation today are the result of federal grants made over the years. For example, because of the 1977 Clean Water Act Amendment to the Federal Water Pollution Control Act of 1972 and the 1987 Clean Water Act Reauthorization Bill, funding for wastewater treatment plants was provided.

Many large sanitation districts, with their multiple plant operations, and an even larger number of single plant operations in smaller communities in operation today are a result of these early environmental laws. Because of these laws, the federal government provided grants of several hundred million dollars to finance construction of wastewater treatment facilities throughout the country.

Many of these locally or federally funded treatment plants are aging; based on our experience, we rate some as dinosaurs. The point is many facilities are facing problems caused by aging equipment, facilities, and infrastructure. Complicating the problems associated with natural aging is the increasing pressure on inadequate older systems to meet demands of increased population and urban growth. Facilities built in the 1960s and 1970s are now 30 to 40 years old; not only are they showing signs of wear and tear, but they simply were not designed to handle the level of growth that has occurred in many municipalities.

Regulations often necessitate a need to upgrade. By matching funds or providing federal money to cover some of the costs, municipalities can take advantage of a window of opportunity to improve their facility at a lower direct cost to the community. Those federal dollars, of course, do come with strings attached; they are to be spent on specific projects in specific areas. On the other hand, many times new regulatory requirements are put in place without the financial assistance needed to implement. When this occurs, either the local community ignores the

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new requirements (until caught and forced to comply) or they face the situation and implement through local tax hikes to pay the cost of compliance.

An example of how a change in regulations can force the issue is demonstrated by the demands made by the Occupational Safety and Health Administration (OSHA) and EPA in their Process Safety Management (PSM)/Risk Management Planning (RMP) regulations. These regulations put the use of elemental chlorine (and other listed hazardous materials) under scrutiny. Moreover, because of these regulations, plant managers throughout the country are forced to choose which side of a double-edged sword cuts their way the most. One edge calls for full compliance with the regulations (analogous to stuffing the regulation through the eye of a needle). The other edge calls for substitution. This means replacing elemental chlorine with a nonlisted hazardous chemical (e.g., hypochlorite) or a physical (ultraviolet irradiation) disinfectant — a very costly undertaking either way.

Note: Many of us who have worked in water and wastewater treatment for years characterize PSM and RMP as the elemental chlorine killer. You have probably heard the old saying: "If you can't do away with something in one way, then regulate it to death."

Note: Changes resulting because of regulatory pressure sometimes mean replacing or changing existing equipment, increased chemical costs (e.g., substituting hypochlorite for chlorine typically increases costs threefold), and could easily involve increased energy and personnel costs. Equipment condition, new technology, and financial concerns are all considerations when upgrades or new processes are chosen. In addition, the safety of the process must be considered because of the demands made by EPA and OSHA. The potential of harm to workers, the community, and the environment are all under study, as are the possible long-term effects of chlorination on the human population.

1.4.3 Privatizing and/or Reengineering[8]

As mentioned, water and wastewater treatment operations are undergoing a new paradigm shift. We explained that this paradigm shift focused on the holistic approach to treating water. The shift is, however, more inclusive. It also includes thinking outside the box. In order to remain efficient and therefore competitive in the real world of operations, water and wastewater facilities have either bought into the new paradigm shift, or been forcibly "shifted" to doing other things (often these other things have little to do with water and wastewater operations).

Our experience has shown that few words conjure up more fear among municipal plant managers than privatization or reengineering. *Privatization* means allowing private enterprise to compete with government in providing public services, such as water and wastewater operations. Existing management, on the other hand, can accomplish reengineering internally or it can be used (and usually is) during the privatization process. *Reengineering* is the systematic transformation of an existing system into a new form to realize quality improvements in operation, system capability, functionality, performance, or evolvability at a lower cost, schedule, or risk to the customer.

Many on-site managers consider privatization and/or reengineering schemes threatening. In the worse case scenario, a private contractor could bid the entire staff out of their jobs. In the best case, privatization and/or re-engineering is often a very real threat that forces on-site managers into workforce cuts, improving efficiency and cutting costs. (At the same time, on-site managers work to ensure the community receives safe drinking water and the facility meets standards and permits. This is done with fewer workers and without injury or accident to workers, the facility, or the environment.)

There are a number of reasons causing local officials to take a hard look at privatization and/or re-engineering.

1. **Decaying infrastructures —** Many water and wastewater operations include water and wastewater infrastructures that date back to the early 1900s. The most recent systems were built with federal funds during the 1970s, and even these now need upgrading or replacing. The EPA recently estimated that the nation's 75,000+ drinking water systems alone would require more than $100 billion in investments over the next 20 years. Wastewater systems will require a similar level of investment.
2. **Mandates —** The federal government has reduced its contributions to local water and wastewater systems over the past 30 years, while at the same time imposing stricter water quality and effluent standards under the Clean Water Act and SDWA. Moreover, as previously mentioned, new unfunded mandated safety regulations, such as OSHA's PSM and EPA's RMP, are expensive to implement using local sources of revenues or state revolving loan funds.
3. **Hidden function —** Earlier we stated that much of the work of water and wastewater treatment is a hidden function. Because of this lack of visibility, it is often difficult for local officials to commit to making the necessary investments in community water and wastewater systems. Simply, the local politicians lack the political will — water pipes and interceptors are not

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Start → Plan → Research → Observe → Analyze → Adapt

FIGURE 1.2 Benchmarking process.

visible and not perceived as immediately critical for adequate funding. It is easier for elected officials to ignore them in favor of expenditures of more visible services, such as police and fire. Additionally, raising water and sewage rates to cover operations and maintenance is not always effected because it is an unpopular move for elected officials. This means that water and sewer rates do not adequately cover the actual cost of providing services in many municipalities.

In many locations throughout the U.S., expenditures on water and wastewater services are the largest facing local governments today. (This is certainly the case for those municipalities struggling to implement the latest storm water requirements). Thus, this area presents a great opportunity for cost savings. Through privatization, water and wastewater companies can take advantage of advanced technology, more flexible management practices, and streamlined procurement and construction practices to lower costs and make the critical improvements more quickly.

1.4.4 Benchmarking

Primarily out of self-preservation (to retain their lucrative positions), many utility directors work against the trend to privatize water, wastewater, and other public operations. Usually the real work to prevent privatization is delegated to the individual managers in charge of each specific operation. Moreover, it can be easily seen that working against privatization by these local managers is also in their own self-interest and in the interest of their workers; their jobs may be at stake.

The question is, of course, how does one go about preventing his water and wastewater operation from being privatized? The answer is rather straightforward and clear: Efficiency must be improved at reduced cost. In the real world, this is easier said than done, but is not impossible. For example, for those facilities under Total Quality Management (TQM), the process can be much easier.

The advantage TQM offers the plant manager is the variety of tools to help plan, develop, and implement water and wastewater efficiency measures. These tools include self-assessments, statistical process control, International Organization for Standards 9000 and 14000, process analysis, quality circle, and benchmarking (see Figure 1.2).

Our focus in this text is on use of the benchmarking tool to improve water and wastewater operation's efficiency. *Benchmarking* is a process for rigorously measuring your performance vs. best-in-class operations, and using the analysis to meet and exceed the best in class.

What benchmarking is:

1. Benchmarking vs. best practices gives water and wastewater operations a way to evaluate their operations overall.
   a. How effective
   b. How cost effective
2. Benchmarking shows plants both how well their operations stack up, and how well those operations are implemented.
3. Benchmarking is an objective-setting process.
4. Benchmarking is a new way of doing business.
5. Benchmarking forces an external view to ensure correctness of objective-setting.
6. Benchmarking forces internal alignment to achieve plant goals.
7. Benchmarking promotes teamwork by directing attention to those practices necessary to remain competitive.

Potential results of benchmarking:

1. Benchmarking may indicate direction of required change rather than specific metrics
   a. Costs must be reduced
   b. Customer satisfaction must be increased
   c. Return on assets must be increased
   d. Improved maintenance
   e. Improved operational practices
2. Best practices are translated into operational units of measure.

Targets:

1. Consideration of available resources converts benchmark findings to targets.
2. A target represents what can realistically be accomplished in a given timeframe.
3. A target can show progress toward benchmark practices and metrics.
4. Quantification of precise targets should be based on achieving benchmark.

Note: Benchmarking can be performance based, process based, or strategy based and can compare financial or operational performance measures, methods or practices, or strategic choices.

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1.4.4.1 Benchmarking: The Process

When forming a benchmarking team, the goal should be to provide a benchmark that evaluates and compares privatized and reengineered water and wastewater treatment operations to your operation. This helps your operation to be more efficient, remain competitive, and make continual improvements. It is important to point out that benchmarking is more than simply setting a performance reference or comparison; it is a way to facilitate learning for continual improvements. The key to the learning process is looking outside one's own plant to other plants that have discovered better ways of achieving improved performance.

1.4.4.1.1 Benchmarking Steps

As shown in Figure 1.2, the benchmarking process consists of five steps.

1. Planning — Managers must select a process (or processes) to be benchmarked. A benchmarking team should be formed. The process of benchmarking must be thoroughly understood and documented. The performance measure for the process should be established (i.e., cost, time, and quality).
2. Research — Information on the best-in-class performer must be determined through research. The information can be derived from the industry's network, industry experts, industry and trade associations, publications, public information, and other award-winning operations.
3. Observation — The observation step is a study of the benchmarking subject's performance level, processes, and practices that have achieved those levels, and other enabling factors.
4. Analysis — In this phase, comparisons in performance levels among facilities are determined. The root causes for the performance gaps are studied. To make accurate and appropriate comparisons, the comparison data must be sorted, controlled for quality, and normalized.
5. Adaptation — This phase is putting what is learned throughout the benchmarking process into action. The findings of the benchmarking study must be communicated to gain acceptance, functional goals must be established, and a plan must be developed. Progress should be monitored and, as required, corrections in the process made.

Note: Benchmarking should be interactive. It should also recalibrate performance measures and improve the process.

1.4.4.1.2 Benchmarking: An Example

To gain better understanding of the benchmarking process, we have provided the following limited example. It is in outline and summary form only — discussion of a full-blown study is beyond the scope of this text. (Although the details described below come from a real study, we have provided a fictitious name for the sanitation district.)

Rachel's Creek Sanitation District

Introduction

In January 1997, Rachel's Creek Sanitation District formed a benchmarking team with the goal of providing a benchmark that evaluates and compares privatized and re-engineered wastewater treatment operations to Rachel's Creek operations in order to be more efficient and remain competitive. After three months of evaluating wastewater facilities using the benchmarking tool, our benchmarking is complete. This report summarizes our findings and should serve as a benchmark by which to compare and evaluate Rachel's Creek Sanitation District operations.

Facilities

41 wastewater treatment plants throughout the U.S.

The benchmarking team focused on the following target areas for comparison:

1. Reengineering
2. Organization
3. Operations and maintenance
   a. Contractual services
   b. Materials and supplies
   c. Sampling and data collection
   d. Maintenance
4. Operational directives
5. Utilities
6. Chemicals
7. Technology
8. Permits
   a. Water quality
   b. Solids quality
   c. Air quality
   d. Odor quality
9. Safety
10. Training and development
11. Process
12. Communication
13. Public relations
14. Reuse
15. Support services
    a. Pretreatment
    b. Collection systems
    c. Procurement

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d. Finance and administration
e. Laboratory
f. Human resources

Summary of Findings:
Our overall evaluation of Rachel's Creek Sanitation District as compared to our benchmarking targets is a good one; that is, we are in good standing as compared to the 41 target facilities we benchmarked with. In the area of safety, we compare quite favorably. Only plant 34, with its own full time safety manager, appeared to be better than we are. We were very competitive with the privatized plants in our usage of chemicals and far ahead of many public plants. We were also competitive in the use of power. Our survey of what other plants are doing to cut power costs showed that we clearly identified those areas of improvement and our current effort to further reduce power costs is on track. We were far ahead in the optimization of our unit processes and we were leaders in the area of odor control.

There were also areas that we need to improve. To the Rachel's Creek employee, reengineering applies to only the treatment department and has been limited to cutting staff while plant practices and organizational practices are outdated and inefficient. Under the reengineering section of this report, we have provided a summary of reengineering efforts at the reengineered plants visited. The experiences of these plants can be used to improve our own reengineering effort. Next is our organization and staffing levels. A private company could reduce the entire treatment department staff by about 18 to 24%. The 18 to 24% are based on number of employees and not costs. In the organization section of this report, organizational models and their staffing levels are provided as guidelines to improving our organization and determining optimum staffing levels. The last big area that we need to improve is in the way we accomplish the work we perform. Our people are not used efficiently because of outdated and inefficient policies and work practices. Methods to improve the way we do work are found throughout this report. We noted that efficient work practices used by private companies allow plants to operate with small staffs.

Overall, Rachel's Creek Sanitation District treatment plants are much better than other public plants. Although some plants may have better equipment, better technology, and cleaner effluents, the costs in labor and materials is much higher than ours. Several of the public plants were in bad condition. Contrary to popular belief, the privately operated plants had good to excellent operations. These plants met permit, complied with safety regulations, maintained plant equipment, and kept the plant clean. Due to their efficiency and low staff, we felt that most of the privately operated plants were better than ours. We agreed this needs to be changed. Using what we learned during our benchmarking effort, we can be just as efficient as a privately operated plant and still maintain our standards of quality.

1.4.5 The Bottom Line on Privatization

Privatization is becoming of greater and greater concern. Governance boards see privatization as a potential way to shift liability and responsibility from the municipality's shoulders, with the attractive bonus of cutting costs. Both water and wastewater facilities face constant pressure to work more efficiently and more cost-effectively with fewer workers to produce a higher quality product; all functions must be value-added. Privatization is increasing, and many municipalities are seriously considering outsourcing part or all of their operations to contractors.

1.5 UPGRADING SECURITY

> You may say Homeland Security is a Y2K problem that doesn't end January 1 of any given year.
>
> **Governor Tom Ridge[9]**

One consequence of the events of September 11 was EPA's directive to establish a Water Protection Task Force to ensure that activities to protect and secure water supply/wastewater treatment infrastructure are comprehensive and carried out expeditiously. Another consequence is a heightened concern among citizens in the U.S. over the security of their critical water and wastewater infrastructure. The nation's water and wastewater infrastructure consisting of several thousand publicly owned water and wastewater treatment plants, more than 100,000 pumping stations, hundreds of thousands of miles of water distribution and sanitary sewers, and another 200,000 miles of storm sewers is one of America's most valuable resources, with treatment and distribution/collection systems valued at more than $2.5 trillion. Wastewater treatment operations taken alone include the sanitary and storm sewers, forming an extensive network that runs near or beneath key buildings and roads, and is contiguous to many communication and transportation networks. Significant damage to the nation's wastewater facilities or collection systems would result in loss of life; catastrophic environmental damage to rivers, lakes, and wetlands; contamination of drinking water supplies; long-term public health impacts; destruction

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of fish and shellfish production; and disruption of commerce, the economy, and our normal way of life.

Governor Tom Ridge points out the security role for the public professional (we interpret this to include water and wastewater professionals):

> Americans should find comfort in knowing that millions of their fellow citizens are working every day to ensure our security at every level — federal, state, county, municipal. These are dedicated professionals who are good at what they do. I've seen it up close, as Governor of Pennsylvania … but there may be gaps in the system. The job of the Office of Homeland Security will be to identify those gaps and work to close them.[10]

It is to shore up the gaps in the system that has driven many water and wastewater facilities to increase security. In its "Water Protection Task Force Alert #IV: What Wastewater Utilities Can Do Now to Guard Against Terrorist and Security Threats,"[11] EPA made several recommendations to increase security and reduce threats from terrorism. The recommendations include:

1. Guarding against unplanned physical intrusion (water and wastewater)
   a. Lock all doors and set alarms at your office, pumping stations, treatment plants, and vaults, and make it a rule that doors are locked and alarms are set.
   b. Limit access to facilities and control access to pumping stations, chemical and fuel storage areas, giving close scrutiny to visitors and contractors.
   c. Post guards at treatment plants, and post "employee only" signs in restricted areas.
   d. Control access to storm sewers.
   e. Secure hatches, metering vaults, manholes, and other access points to the sanitary collection system.
   f. Increase lighting in parking lots, treatment bays, and other areas with limited staffing.
   g. Control access to computer networks and control systems, and change the passwords frequently.
   h. Do not leave keys in equipment or vehicles at any time.
2. Making security a priority for employees
   a. Conduct background security checks on employees at hiring and periodically thereafter.
   b. Develop a security program with written plans and train employees frequently.
   c. Ensure all employees are aware of communications protocols with relevant law enforcement, public health, environmental protection, and emergency response organizations.
   d. Ensure that employees are fully aware of the importance of vigilance and the seriousness of breaches in security, and make note of unaccompanied strangers on the site and immediately notify designated security officers or local law enforcement agencies.
   e. Consider varying the timing of operational procedures if possible in case someone is watching the pattern changes.
   f. Upon the dismissal of an employee, change passcodes and make sure keys and access cards are returned.
   g. Provide customer service staff with training and checklists of how to handle a threat if it is called in.
3. Coordinating actions for effective emergency response
   a. Review existing emergency response plans, and ensure they are current and relevant.
   b. Make sure employees have necessary training in emergency operating procedures.
   c. Develop clear protocols and chains-of-command for reporting and responding to threats along with relevant emergency, law enforcement, environmental, public health officials, consumers, and the media. Practice the emergency protocols regularly.
   d. Ensure key utility personnel (both on and off duty) have access to crucial telephone numbers and contact information at all times. Keep the call list up to date.
   e. Develop close relationships with local law enforcement agencies, and make sure they know where critical assets are located. Request they add your facilities to their routine rounds.
   f. Work with local industries to ensure that their pretreatment facilities are secure.
   g. Report to county or state health officials any illness among the employees that might be associated with wastewater contamination.
   h. Report criminal threats, suspicious behavior, or attacks on wastewater utilities immediately to law enforcement officials and the relevant field office of the Federal Bureau of Investigation.
4. Investing in security and infrastructure improvements
   a. Assess the vulnerability of collection/distribution system, major pumping stations, water and wastewater treatment plants,

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chemical and fuel storage areas, outfall pipes, and other key infrastructure elements.

b. Assess the vulnerability of the storm water collection system. Determine where large pipes run near or beneath government buildings, banks, commercial districts, industrial facilities, or are contiguous with major communication and transportation networks.
c. Move as quickly as possible with the most obvious and cost-effective physical improvements, such as perimeter fences, security lighting, tamper-proofing manhole covers and valve boxes, etc.
d. Improve computer system and remote operational security.
e. Use local citizen watches.
f. Seek financing for more expensive and comprehensive system improvements.

1.5.1 The Bottom Line on Security

Again, when it comes to the security of our nation and even of water and wastewater treatment facilities, few have summed it better than Governor Ridge:

> Now, obviously, the further removed we get from September 11, I think the natural tendency is to let down our guard. Unfortunately, we cannot do that. The government will continue to do everything we can to find and stop those who seek to harm us. And I believe we owe it to the American people to remind them that they must be vigilant, as well.[10]

1.6 TECHNICAL MANAGEMENT VS. PROFESSIONAL MANAGEMENT

Water treatment operations management is management that is directed toward providing water of the right quality, in the right quantity, at the right place, at the right time, and at the right price to meet various demands. Wastewater treatment management is directed toward providing treatment of incoming raw influent (no matter what the quantity), at the right time, to meet regulatory requirements, and at the right price to meet various requirements.

The techniques of management are manifold both in water resource management and wastewater treatment operations. In water treatment operations, for example, management techniques may include:

Storage to detain surplus water available at one time of the year for use later, transportation facilities to move water from one place to another, manipulation of the pricing structure for water to reduce demand, use of changes in legal systems to make better use of the supplies available, introduction of techniques to make more water available through watershed management, cloud seeding, desalination of saline or brackish water, or area-wide educational programs to teach conservation or reuse of water.[12]

Many of the management techniques employed in water treatment operations are also employed in wastewater treatment. In addition, wastewater treatment operations employ management techniques that may include upgrading present systems for nutrient removal, reuse of process residuals in an earth-friendly manner, and area-wide educational programs to teach proper domestic and industrial waste disposal practices.

Whether managing a waterworks or wastewater treatment plant, the manager, in regards to expertise, must be a well-rounded, highly skilled individual. No one questions the need for incorporation of these highly-trained practitioners — well-versed in the disciplines of sanitary engineering, biology, chemistry, hydrology, environmental science, safety principles, accountants, auditors, technical aspects, and operations — in both professions. Based on personal experience, however, engineers, biologists, chemists, and others with no formal management training are often hindered (limited) in their ability to solve the complex management problems currently facing both industries.

There are those who will view this opinion with some disdain. However, in the current environment where privatization, the need for upgrading security, and other pressing concerns are present, skilled management professionals are needed to manage and mitigate these problems.

1.7 CHAPTER REVIEW QUESTIONS AND PROBLEMS

Answers to chapter review questions are found in Appendix A.

1.1. Define paradigm as used in this text.
1.2. Define paradigm shift as used in this text.
1.3. List five elements of the multiple-barrier approach.
1.4. Explain the following: Water service delivery remains one of the hidden functions of local government.
1.5. Fill in the blank: _____ drinking water standards are not enforceable.
1.6. Explain the difference between privatization and reengineering.
1.7. Define benchmarking.
1.8. List the five benchmarking steps.

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2 Water and Wastewater Operators and Their Roles

Our planet is shrouded in water, and yet 8 million children under the age of five will die this year from lack of safe water.

United Nations Environmental Program

2.1 WATER AND WASTEWATER OPERATORS

To begin our discussion of water and wastewater operators, it is important that we point out a few significant factors.

- Employment as a water and wastewater operator is concentrated in local government and private water supply and sanitary services companies.
- Postsecondary training is increasingly an asset as the number of regulated contaminants grows and treatment unit processes become more complex.
- Operators must pass examinations certifying that they are capable of overseeing various treatment processes.
- Operators have a relatively high incidence of on-the-job (OTJ) injuries.

To properly operate a water treatment and distribution and/or a wastewater treatment and collection system usually requires a team of highly skilled personnel filling a variety of job classifications. Typical positions include plant manager/plant superintendent, chief operator, lead operator, operator, maintenance operator, distribution and/or interceptor system technicians, assistant operators, laboratory professionals, and clerical personnel, to list just a few.

Beyond the distinct job classification titles, over the years those operating water and wastewater plants have been called by a variety of titles. These include water jockey, practitioner of water, purveyor of water, sewer rat, or just plain water or wastewater operator. Based on our experience we have come up with a title that perhaps more closely characterizes what the water and wastewater operator really is: a jack-of-all-trades. This characterization seems only fitting when you take into account the knowledge and skills required of operators to properly perform their assigned duties. Moreover, operating the plant or distribution/collection system is one thing; taking samples, operating equipment, monitoring conditions, and determining settings for chemical feed systems and high-pressure pumps, along with performing laboratory tests and recording the results in the plant daily operating log is another.

It is, however, the non-typical functions, the diverse functions, and the off-the-wall functions that cause us to describe operators as jacks-of-all-trades. For example, in addition to their normal, routine, daily operating duties, operators may be called upon to make emergency repairs to systems (e.g., making a welding repair to a vital piece of machinery to keep the plant or unit process on line), perform material handling operations, make chemical additions to process flow; respond to hazardous materials emergencies, make confined space entries, perform site landscaping duties, and carry out several other assorted functions. Remember, the plant operator's job is to keep the plant running and to make permit. Keeping the plant running, the flow flowing, and making permit — no matter what — requires not only talent but also the performance of a wide range of functions, many of which are not called for in written job descriptions.[1]

2.2 SETTING THE RECORD STRAIGHT

Based on our experience, we have found that most people either have a preconceived notion as to what water and wastewater operations are all about, or they have nary a clue. On the one hand, we understand that clean water is essential for everyday life. Moreover, we have at least a vague concept that water treatment plants and water operators treat water to make it safe for consumption. On the other hand, when it comes to wastewater treatment and system operations, many of us have an ingrained image of a sewer system managed and run by a bunch of sewer rats. Others give wastewater and its treatment and the folks who treat it no thought at all (that is, unless they are irate ratepayers upset at the cost of wastewater service).

Typically, the average person has other misconceptions about water and wastewater operations. For example, very few people can identify the exact source supply of their drinking water. Is it pumped from wells, rivers, or streams to water treatment plants? Similarly, where is it treated and distributed to customers? The average person is clueless as to the ultimate fate of wastewater. Once the

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toilet is flushed, it is out of sight out of mind and that is that.

Beyond the few functions we have pointed out up to this point, what exactly is it those water and wastewater operators, the 90,000+ jacks-of-all-trades in the U.S. do? Operators in both water and wastewater treatment systems control unit processes and equipment to remove or destroy harmful materials, chemical compounds, and microorganisms from the water. They also control pumps, valves, and other processing equipment (including a wide array of computerized systems) to convey the water or wastewater through the various treatment processes (unit processes), and dispose (or reuse) of the removed solids (waste materials: sludge or biosolids). Operators also read, interpret, and adjust meters and gauges to make sure plant equipment and processes are working properly. They operate chemical-feeding devices, take samples of the water or wastewater, perform chemical and biological laboratory analyses, and adjust the amount of chemicals, such as chlorine, in the water and wastestream. They use a variety of instruments to sample and measure water quality, and common hand and power tools to make repairs and adjustments. Operators also make minor repairs to valves, pumps, basic electrical equipment and other equipment. (Electrical work should only be accomplished by qualified personnel.)

As mentioned, water and wastewater system operators increasingly rely on computers to help monitor equipment, store sampling results, make process-control decisions, schedule and record maintenance activities, and produce reports. Computer-operated automatic sampling devices are beginning to gain widespread acceptance and use in both industries, especially at the larger facilities. When a system malfunction occurs, operators may use system computers to determine the cause and the solution to the problem.

2.2.1 The Computer-Literate Jack

At many modern water and wastewater treatment plants operators are required to perform skilled treatment plant operations work and to monitor, operate, adjust and regulate a computer-based treatment process. In addition, the operator is also required to operate and monitor electrical, mechanical, and electronic processing and security equipment through central and remote terminal locations in a solids processing, water purification or wastewater treatment plant. In those treatment facilities that are not completely or partially automated, computer-controlled computers are used in other applications, such as in clerical applications and in a computer maintenance management system (CMMS). The operator must be qualified to operate and navigate such computer systems.

Typical examples of the computer-literate operator's work (for illustrative purposes only) are provided as follows:[2]

- Monitors, adjusts, starts, and stops automated water treatment processes and emergency response systems to maintain a safe and efficient water treatment operation; monitors treatment plant processing equipment and systems to identify malfunctions and their probable cause following prescribed procedures; places equipment in or out of service or redirects processes around failed equipment; following prescribed procedures monitors and starts process related equipment, such as boilers, to maintain process and permit objectives; refers difficult equipment maintenance problems and malfunctions to supervisor; monitors the system through a process integrated control terminal or remote station terminal to assure control devices are making proper treatment adjustments; operates the central control terminal keyboard to perform backup adjustments to such treatment processes as influent and effluent pumping, chemical feed, sedimentation, and disinfection; monitors specific treatment processes and security systems at assigned remote plant stations; observes and reviews terminal screen display of graphs, grids, charts and digital readouts to determine process efficiency; responds to visual and audible alarms and indicators that indicate deviations from normal treatment processes and chemical hazards; identifies false alarms and other indicators that do not require immediate response; alerts remote control locations to respond to alarms indicating trouble in that area; performs alarm investigations.
- Switches over to semiautomatic or manual control when the computer control system is not properly controlling the treatment process; off-scans a malfunctioning field sensor point and inserts data obtained from field in order to maintain computer control; controls automated mechanical and electrical treatment processes through the computer keyboard when computer programs have failed; performs field tours to take readings when problems cannot be corrected through the computer keyboard; makes regular field tours of the plant to observe physical conditions; manually controls processes when necessary.
- Determines and changes the amount of chemicals to be added for the amount of water, wastewater, or biosolids to be treated; takes periodic samples of treated residuals, biosolids processing

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products and by-products, clean water, or wastewater for laboratory analysis; receives, stores, handles and applies chemicals and other supplies needed for operation of assigned station; maintains inventory records of suppliers on hand and quantities used; prepares and submits daily shift operational reports; records daily activities in plant operation log, computer database or from a computer terminal; changes chemical feed tanks, chlorine cylinders, and feed systems; flushes clogged feed and sampling lines.

- Notes any malfunctioning equipment; makes minor adjustments when required; reports major malfunctions to higher-level operator and enters maintenance and related task information into a CMMS and processes work requests for skilled maintenance personnel.
- Performs routine mechanical maintenance such as packing valves, adjusting belts, and replacing shear pins and air filters; lubricates equipment by applying grease and adding oil; changes and cleans strainers; drains condensate from pressure vessels, gearboxes, and drip traps; performs minor electrical maintenance such as replacing bulbs and resetting low voltage circuit switches; prepares equipment for maintenance crews by unblocking pipelines, pumps, and isolating and draining tanks; checks equipment as part of a preventive and predictive maintenance program; reports more complex mechanical-electrical problems to supervisors.
- Responds, in a safe manner, to chlorine leaks and chemical spills in compliance with the Occupational Safety and Health Admimistration's (OSHA) Hazardous Waste Operational and Emergency Response (29 CFR 1910.120) requirements and with plant specific emergency response procedures; participates in chlorine and other chemical emergency response drills.
- Prepares operational and maintenance reports as required, including flow and treatment information; changes charts and maintains recording equipment; utilizes system and other software packages to generate reports and charts and graphs of flow and treatment status and trends; maintains workplace housekeeping.

2.2.2 Plant Operators as Emergency Responders

As mentioned, occasionally operators must work under emergency conditions. Sometimes these emergency conditions are operational and not necessarily life threatening. A good example occurs during a rain event when there may be a temporary loss of electrical power and large amounts of liquid waste flow into sewers, exceeding a plant's treatment capacity. Emergencies can also be caused by conditions inside a plant, such as oxygen deficiency within a confined space or exposure to toxic and/or explosive off-gases such as hydrogen sulfide and methane. To handle these conditions, operators are trained to make an emergency management response and use special safety equipment and procedures to protect co-workers, public health, the facility, and the environment. During emergencies, operators may work under extreme pressure to correct problems as quickly as possible. These periods may create dangerous working conditions; operators must be extremely careful and cautious.

Operators who must aggressively respond to hazardous chemical leaks or spills (e.g., enter a chlorine gas filled room and install chlorine repair kit B on a damaged 1-ton cylinder to stop the leak) must possess a Hazardous Materials (HAZMAT) emergency response technician 24-hour certification. Additionally, many facilities, where elemental chlorine is used for disinfection, odor control, or other process applications, require operators to possess an appropriate certified pesticide applicator training completion certificate. Because of OSHA's specific confined space requirement whereby a standby rescue team for entrants must be available, many plants require operators to hold and maintain cardiopulmonary resuscitation/first aid certification.

Note: It is important to point out that many wastewater facilities have substituted elemental chlorine with sodium or calcium hypochlorite, ozone, or ultraviolet irradiation because of the stringent requirements of OSHA's Process Safety Management Standard (29 CFR 1910.119) and the U.S. Environmental Protection Agency's (EPA) Risk Management Program. This is not the case in most water treatment operations. In water treatment systems, elemental chlorine is still employed because it provides chlorine residual that is important in maintaining safe drinking water supplies, especially throughout lengthy distribution systems.

2.2.3 Operator Duties, Numbers, and Working Conditions

The specific duties of plant operators depend on the type and size of plant. In smaller plants, one operator may control all machinery, perform sampling and lab analyses, keep records, handle customer complaints, troubleshoot and make repairs, or perform routine maintenance. In some locations, operators may handle both water treatment and wastewater treatment operations. In larger plants with many employees, operators may be more specialized and only monitor one unit process (e.g., a solids handling

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operator who operates and monitors an incinerator). Along with treatment operators, plant staffing may include environmentalists, biologists, chemists, engineers, laboratory technicians, maintenance operators, supervisors, clerical help, and various assistants.

In the U.S., notwithstanding a certain amount of downsizing brought on by privatization activites, employment opportunities for water and wastewater operators have increased in number. The number of operators has increased because of the ongoing construction of new water and wastewater and solids handling facilities. In addition, operator jobs have increased because of water pollution standards that have become increasingly more stringent since adoption of two major federal environmental regulations: The Clean Water Act of 1972 (and subsequent amendments), which implemented a national system of regulation on the discharge of pollutants, and the Safe Drinking Water Act (SDWA) of 1974, which established standards for drinking water.

Operators are often hired in industrial facilities to monitor or pretreat wastes before discharge to municipal treatment plants. These wastes must meet certain minimum standards to ensure that they have been adequately pretreated and will not damage municipal treatment facilities. Municipal water treatment plants also must meet stringent drinking water standards. This often means that additional qualified staff members must be hired to monitor and treat/remove specific contaminants. Complicating the problem is the fact that the list of contaminants regulated by these regulations has grown over time. For example, the 1996 SDWA Amendments include standards for monitoring *Giardia* and *Cryptosporidium*, two biological organisms (protozoans) that cause health problems. Operators must be familiar with the guidelines established by federal regulations and how they affect their plant. In addition to federal regulations, operators must be aware of any guidelines imposed by the state or locality in which the treatment process operates.

Another unique factor related to water and wastewater operators is their working conditions. Water and wastewater treatment plant operators work indoors and outdoors in all kinds of weather. Operators' work is physically demanding and often is performed in unclean locations (hence, the emanation of the descriptive but inappropriate title, sewer rat). They are exposed to slippery walkways; vapors; odors; heat; dust; and noise from motors, pumps, engines, and generators. They work with hazardous chemicals. In water and wastewater plants, operators may be exposed to many bacterial and viral conditions. As mentioned, dangerous gases, such as methane and hydrogen sulfide, could be present so they need to use proper safety gear.

Operators generally work a 5-day, 40-hour week. However, many treatment plants are in operation 24/7, and operators may have to work nights, weekends, holidays, or rotating shifts. Some overtime is occasionally required in emergencies.

Over the years, statistical reports have related historical evidence showing that the water and wastewater industry is an extremely unsafe occupational field. This less than stellar safety performance has continued to deteriorate even in the age of the Occupational Safety and Health Act of 1970.

The question is why is the water and wastewater treatment industry's OTJ injury rate so high? Several reasons help to explain this high injury rate. First, all of the major classifications or hazards exist at water and wastewater treatment plants (typical exception radioactivity):

- Oxygen deficiency
- Physical injuries
- Toxic gases and vapors
- Infections
- Fire
- Explosion
- Electrocution

Along with all the major classifications of hazards, other factors cause the high incidence of injury in the water and wastewater industry. Some of these can be attributed to:

- Complex treatment systems
- Shift work
- New employees
- Liberal workers' compensation laws
- Absence of safety laws
- Absence of safe work practices and safety programs

Experience has shown that a lack of well-managed safety programs and safe work practices are major factors causing the water and wastewater industry's high incidence of OTJ injuries.

2.3 OPERATOR CERTIFICATION/LICENSURE

A high school diploma or its equivalency usually is required as the entry-level credential to become a water or wastewater treatment plant operator-in-training. Operators need mechanical aptitude and should be competent in basic mathematics, chemistry, and biology. They must have the ability to apply data to formulas of treatment requirements, flow levels, and concentration levels. Some basic familiarity with computers also is necessary because of the present trend toward computer-controlled equipment and more sophisticated instrumentation. Certain operator positions, particularly in larger cities, are covered by civil service regulations. Applicants for these positions may be required

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to pass a written examination testing mathematics skills, mechanical aptitude, and general intelligence.

Because treatment operations are becoming more complex, completion of an associate's degree or 1-year certificate program in water quality and wastewater treatment technology is highly recommended. These credentials increase an applicant's chances for both employment and promotion. Advanced training programs are offered throughout the country. They provide a good general through advanced training on water and wastewater treatment processes, as well as basic preparation for becoming a licensed operator. They also offer a wide range of computer training courses.

New water and wastewater operators-in-training typically start out as attendants or assistants and learn the practical aspects of their job under the direction of an experienced operator. They learn by observing, show-and-tell, and doing routine tasks. These tasks can include recording meter readings; taking samples of liquid waste and sludge; and performing simple maintenance and repair work on pumps, electrical motors, valves, and other plant or system equipment. Larger treatment plants generally combine this OTJ training with formal classroom or self-paced study programs. Some large sanitation districts operate their own 3- to 4-year apprenticeship schools. In some of these programs, each year of apprenticeship school completed not only prepares the operator for the next level of certification or licensure, but also satisfies a requirement for advancement to the next higher pay grade.

The SDWA Amendments of 1996, enforced by the EPA, specify national minimum standards for certification (licensure) and recertification of operators of community and nontransient, noncommunity water systems. As a result, operators must pass an examination to certify that they are capable of overseeing water and wastewater treatment operations. There are different levels of certification depending on the operator's experience and training. Higher certification levels qualify the operator for a wider variety of treatment processes. Certification requirements vary by state and by size of treatment plants. Although relocation may mean having to become certified in a new location, many states accept other states' certifications.

In an attempt to ensure the currentness of training and qualifications and to improve operators' skills and knowledge, most state drinking water and water pollution control agencies offer on-going training courses. These courses cover principles of treatment processes and process control methods, laboratory practices, maintenance procedures, management skills, collection system operation, general safe work practices, chlorination procedures, sedimentation, biological treatment, sludge/biosolids treatment, biosolids land application and disposal, and flow measurements. Correspondence courses covering both water and wastewater operations and preparation for state licensure examinations are provided by various state and local agencies. Many employers provide tuition assistance for formal college training.

Whether received from formal or informal sources, training provided for or obtained by water and wastewater operators must include coverage of very specific subject/topic areas. Though much of their training is similar or the same, Tables 2.1 and 2.2 list many of the specific specialized topics waterworks and wastewater operators are expected to have a fundamental knowledge.

Note: It is important to note that both water and wastewater operators must have fundamental knowledge of basic science and math operations.

Note: For many water and wastewater operators, crossover training or overlapping training is common practice.

TABLE 2.1
Specialized Topics for Wastewater Operators

Wastewater math	Fecal coliform testing
Troubleshooting techniques	Recordkeeping
Preliminary treatment	Flow measurement
Sedimentation	Sludge dewatering
Ponds	Drying beds
Trickling filters	Centrifuges
Rotating biological contactors	Vacuum filtration
Activated sludge	Pressure filtration
Chemical treatment	Sludge incineration
Disinfection	Land application of biosolids
Solids thickening	Laboratory procedures
Solids stabilization	General safety

TABLE 2.2
Specialized Topics for Waterworks Operators

Chemical addition	Hydraulics — math
Chemical feeders	Laboratory practices
Chemical feeders — math	Measuring and control
Clarification	Piping and valves
Coagulation — flocculation	Public health
Corrosion control	Pumps
Disinfection	Recordkeeping
Disinfection — math	General science
Basic electricity and controls	Electric motors
Filtration	Finances
Filtration — math	Storage
Fluoridation	Leak detection
Fluoridation — math	Hydrants
General safe work practices	Cross connection control and backflow
Bacteriology	Stream ecology

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2.4 CHAPTER REVIEW QUESTIONS AND PROBLEMS

2.1. Briefly explain the causal factors behind the high incidence of OTJ injuries for water and wastewater operators.
2.2. Why is computer literacy so important in operating a modern water and wastewater treatment system?
2.3. Define CMMS.
2.4. List the necessary training requirement for HAZMAT responders.
2.5. Specify the national minimum standard for certification (licensure) and recertification for water and wastewater operators.

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3 Water and Wastewater References, Models, and Terminology

Living things depend on water, but water does not depend on living things. It has a life of its own.

E.C. Pielou[1]

3.1 SETTING THE STAGE

This handbook is a compilation or summary of information available in many expert sources. While we have attempted to cover all aspects of water and wastewater treatment system operation, let us point out that no one single handbook has all the information or all the answers. Moreover, because of the physical limits of any written text, some topics are only given cursory exposure and limited coverage. For those individuals seeking a more in depth treatment of specific topics germane to water and wastewater treatment system operations, we recommend consulting one or more of the references listed in Table 3.1, and any of the many other outstanding references referred to throughout this text.

3.2 TREATMENT PROCESS MODELS

Figure 3.1 shows a basic schematic of the water treatment process. Other unit processes used in treatment of water (e.g., fluoridation) are not represented in Figure 3.1; we discuss many of the other unit processes in detail within the handbook. Figure 3.2 shows a basic schematic or model of a wastewater treatment process that provides primary and secondary treatment using the activated sludge process. In secondary treatment (which provides biochemical oxygen demand removal beyond what is achievable by simple sedimentation), three approaches are commonly used: trickling filter, activated sludge, and oxidation ponds. We discuss these systems in detail later in the text. We also discuss biological nutrient removal and standard tertiary or advanced wastewater treatment.

The purpose of the models shown in the figures and their subsequent renditions in later chapters is to allow readers to visually follow the water and wastewater treatment process step-by-step as we present it later in the written material. Figure 3.1 and Figure 3.2 help you understand how all the various unit processes sequentially follow and tie into each other. Thus, in chapters dealing with unit processes, we show Figures 3.1 and Figure 3.2 with the applicable process under discussion added to any previous processes. In essence, what we are doing is starting with a blank diagram and filling in unit processes as we progress. We have found that beginning certain chapters in this manner is important because the water and wastewater treatment process is a series of individual steps (unit processes) that treat the raw water or wastewater as it makes its way through the entire process. This format simply provides a pictorial presentation along with pertinent written information, enhancing the learning process.

3.3 KEY TERMS USED IN WATERWORKS AND WASTEWATER OPERATIONS

In order to learn water and wastewater treatment operations (or any other technology for that matter), you must master the language associated with the technology.

Each technology has its own terms with its own accompanying definitions. Many of the terms used in water and wastewater treatment are unique; others combine words from many different technologies and professions. One thing is certain: water and wastewater operators without a clear understanding of the terms related to their profession are ill-equipped to perform their duties in the manner required.

Usually a handbook or text like this one includes a glossary of terms at the end of the work. In this handbook we list and define many of the terms used right up front. Our experience shows that an early introduction to keywords is a benefit to readers. An up-front introduction to key terms facilitates a more orderly, logical, systematic learning activity. Those terms not defined in this section are defined as they appear in the text.

Note: A short quiz on many of the following terms follows the end of this chapter.

3.3.1 Terminology and Definitions

Absorb to take in. Many things absorb water.

Acid rain the acidic rainfall that results when rain combines with sulfur oxides emissions from combustion of fossil fuels (e.g., coal).

Acre-feet (acre-foot) an expression of water quantity. One acre-foot will cover one acre of ground 1 ft deep. An acre-foot contains 43,560 ft^3, 1,233 m^3, or 325,829 gal (U.S.). Also abbreviated as ac-ft.

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TABLE 3.1
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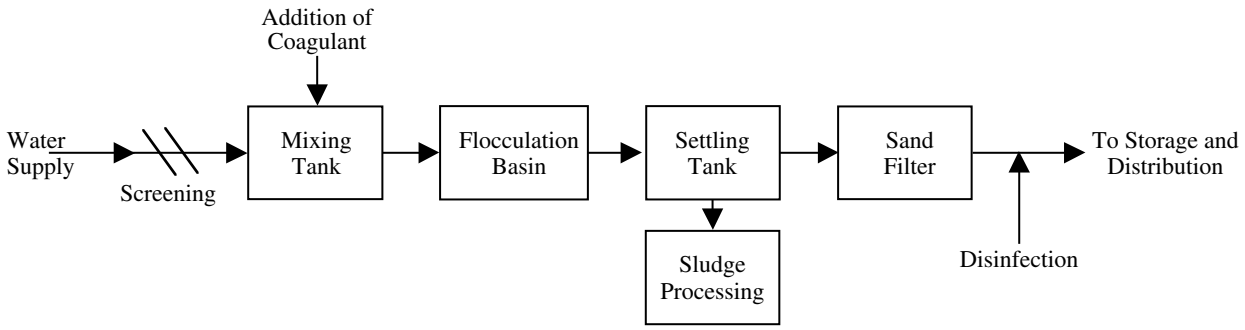

FIGURE 3.1 The water treatment model. (From Spellman, F.R., *The Handbook for Waterworks Operator Certification,* Vol. 1, Technomic Publ., Lancaster, PA, 2001.)

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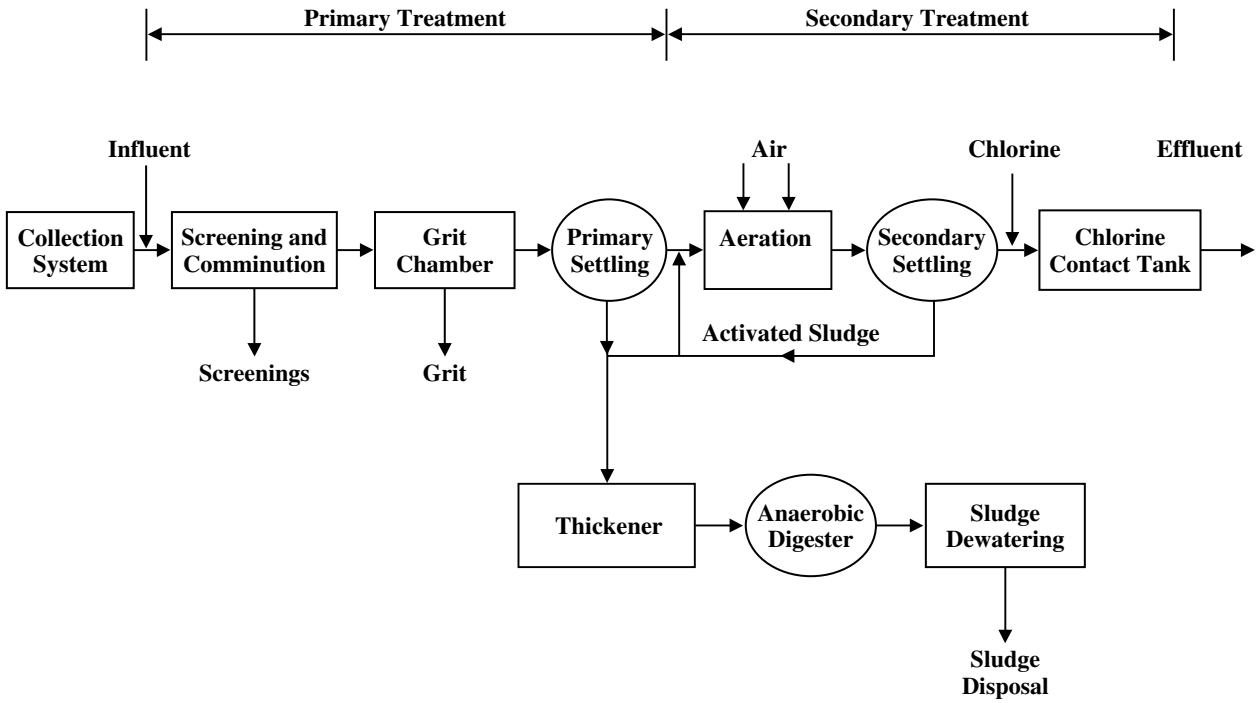

FIGURE 3.2 Schematic of conventional wastewater treatment process. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Activated carbon derived from vegetable or animal materials by roasting in a vacuum furnace. Its porous nature gives it a very high surface area per unit mass, as much as 1,000 m^2/g, which is 10 million times the surface area of 1 g of water in an open container. Used in adsorption (see definition), activated carbon adsorbs substances that are not or are only slightly adsorbed by other methods.

Activated sludge the solids formed when microorganisms are used to treat wastewater using the activated sludge treatment process. It includes organisms, accumulated food materials, and waste products from the aerobic decomposition process.

Advanced wastewater treatment treatment technology to produce an extremely high-quality discharge.

Adsorption the adhesion of a substance to the surface of a solid or liquid. Adsorption is often used to extract pollutants by causing them to attach to such adsorbents as activated carbon or silica gel. Hydrophobic (water-repulsing) adsorbents are used to extract oil from waterways in oil spills.

Aeration the process of bubbling air through a solution, sometimes cleaning water of impurities by exposure to air.

Aerobic conditions in which free, elemental oxygen is present. Also used to describe organisms, biological activity, or treatment processes that require free oxygen.

Agglomeration floc particles colliding and gathering into a larger settleable mass.

Air gap the air space between the free-flowing discharge end of a supply pipe and an unpressurized receiving vessel.

Algae bloom a phenomenon whereby excessive nutrients within a river, stream, or lake causes an explosion of plant life that results in the depletion of the oxygen in the water needed by fish and other aquatic life. Algae bloom is usually the result of urban runoff (of lawn fertilizers, etc.). The potential tragedy is that of a "fish kill," where the stream life dies in one mass execution.

Alum aluminum sulfate, a standard coagulant used in water treatment.

Ambient the expected natural conditions that occur in water unaffected or uninfluenced by human activities.

Anaerobic conditions in which no oxygen (free or combined) is available. Also used to describe organisms, biological activity, or treatment processes that function in the absence of oxygen.

Anoxic conditions in which no free, elemental oxygen is present. The only source of oxygen is combined oxygen, such as that found in nitrate com-

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pounds. Also used to describe biological activity of treatment processes that function only in the presence of combined oxygen.

Aquifer a water-bearing stratum of permeable rock, sand, or gravel.

Aquifer system a heterogeneous body of introduced permeable and less permeable material that acts as a water-yielding hydraulic unit of regional extent.

Artesian water a well tapping a confined or artesian aquifer in which the static water level stands above the top of the aquifer. The term is sometimes used to include all wells tapping confined water. Wells with water level above the water table are said to have positive artesian head (pressure), and those with water level below the water table have negative artesian head.

Average monthly discharge limitation the highest allowable discharge over a calendar month.

Average weekly discharge limitation the highest allowable discharge over a calendar week.

Backflow reversal of flow when pressure in a service connection exceeds the pressure in the distribution main.

Backwash fluidizing filter media with water, air, or a combination of the two so that individual grains can be cleaned of the material that has accumulated during the filter run.

Bacteria any of a number of one-celled organisms, some of which cause disease.

Bar screen a series of bars formed into a grid used to screen out large debris from influent flow.

Base a substance that has a pH value between 7 and 14.

Basin a groundwater reservoir defined by the overlying land surface and underlying aquifers that contain water stored in the reservoir.

Beneficial use of water the use of water for any beneficial purpose. Such uses include domestic use, irrigation, recreation, fish and wildlife, fire protection, navigation, power, industrial use, etc. The benefit varies from one location to another and by custom. What constitutes beneficial use is often defined by statute or court decisions.

Biochemical oxygen demand (BOD) the oxygen used in meeting the metabolic needs of aerobic microorganisms in water rich in organic matter.

Biosolids from (1977) solid organic matter recovered from a sewage treatment process and used especially as fertilizer (or soil amendment); usually used in plural (from *Merriam-Webster's Collegiate Dictionary*, 10th ed., 1998).

Note: In this text, biosolids is used in many places (activated sludge being the exception) to replace the standard term sludge. The authors view the term sludge as an ugly, inappropriate four-letter word to describe biosolids. Biosolids is a product that can be reused; it has some value. Because biosolids has value, it certainly should not be classified as a waste product, and when biosolids for beneficial reuse is addressed, it is made clear that it is not.

Biota all the species of plants and animals indigenous to a certain area.

Boiling point the temperature at which a liquid boils. The temperature at which the vapor pressure of a liquid equals the pressure on its surface. If the pressure of the liquid varies, the actual boiling point varies. The boiling point of water is 212°F or 100°C.

Breakpoint point at which chlorine dosage satisfies chlorine demand.

Breakthrough in filtering, when unwanted materials start to pass through the filter.

Buffer a substance or solution that resists changes in pH.

Calcium carbonate compound principally responsible for hardness.

Calcium hardness portion of total hardness caused by calcium compounds.

Carbonaceous biochemical oxygen demand ($CBOD_5$) the amount of biochemical oxygen demand that can be attributed to carbonaceous material.

Carbonate hardness caused primarily by compounds containing carbonate.

Chemical oxygen demand (COD) the amount of chemically oxidizable materials present in the wastewater.

Chlorination disinfection of water using chlorine as the oxidizing agent.

Clarifier a device designed to permit solids to settle or rise and be separated from the flow. Also known as a settling tank or sedimentation basin.

Coagulation the neutralization of the charges of colloidal matter.

Coliform a type of bacteria used to indicate possible human or animal contamination of water.

Combined sewer a collection system that carries both wastewater and stormwater flows.

Comminution a process to shred solids into smaller, less harmful particles.

Composite sample a combination of individual samples taken in proportion to flow.

Connate water pressurized water trapped in the pore spaces of sedimentary rock at the time it was deposited. It is usually highly mineralized.

Consumptive use (1) the quantity of water absorbed by crops and transpired or used directly in the building of plant tissue, together with the water

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evaporated from the cropped area; (2) the quantity of water transpired and evaporated from a cropped area or the normal loss of water from the soil by evaporation and plant transpiration; (3) the quantity of water discharged to the atmosphere or incorporated in the products of the process in connection with vegetative growth, food processing, or an industrial process.

Contamination (water) damage to the quality of water sources by sewage, industrial waste, or other material.

Cross-connection a connection between a storm drain system and a sanitary collection system, between two sections of a collection system to handle anticipated overloads of one system, or between drinking (potable) water and an unsafe water supply or sanitary collection system.

Daily discharge the discharge of a pollutant measured during a calendar day or any 24-hour period that reasonably represents a calendar day for the purposes of sampling. Limitations expressed as weight are total mass (weight) discharged over the day. Limitations expressed in other units are average measurement of the day.

Daily maximum discharge the highest allowable values for a daily discharge.

Darcy's Law an equation for the computation of the quantity of water flowing through porous media. Darcy's Law assumes that the flow is laminar and that inertia can be neglected. The law states that the rate of viscous flow of homogenous fluids through isotropic porous media is proportional to, and in the direction of, the hydraulic gradient.

Detention time the theoretical time water remains in a tank at a give flow rate.

Dewatering the removal or separation of a portion of water present in a sludge or slurry.

Diffusion the process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

Discharge monitoring report (DMR) the monthly report required by the treatment plant's National Pollutant Discharge Elimination System (NPDES) discharge permit.

Disinfection water treatment process that kills pathogenic organisms.

Disinfection by-products (DBPs) chemical compounds formed by the reaction of disinfectant with organic compounds in water.

Dissolved oxygen (DO) the amount of oxygen dissolved in water or sewage. Concentrations of less than 5 ppm can limit aquatic life or cause offensive odors. Excessive organic matter present in water because of inadequate waste treatment and runoff from agricultural or urban land generally causes low DO.

Dissolved solids the total amount of dissolved inorganic material contained in water or wastes. Excessive dissolved solids make water unsuitable for drinking or industrial uses.

Domestic consumption (use) water used for household purposes such as washing, food preparation, and showers. The quantity (or quantity per capita) of water consumed in a municipality or district for domestic uses or purposes during a given period, it sometimes encompasses all uses, including the quantity wasted, lost, or otherwise unaccounted for.

Drawdown lowering the water level by pumping. It is measured in feet for a given quantity of water pumped during a specified period, or after the pumping level has become constant.

Drinking water standards established by state agencies, U.S. Public Health Service, and Environmental Protection Agency (EPA) for drinking water in the U.S..

Effluent something that flows out, usually a polluting gas or liquid discharge.

Effluent limitation any restriction imposed by the regulatory agency on quantities, discharge rates, or concentrations of pollutants discharged from point sources into state waters.

Energy in scientific terms, the ability or capacity of doing work. Various forms of energy include kinetic, potential, thermal, nuclear, rotational, and electromagnetic. One form of energy may be changed to another, as when coal is burned to produce steam to drive a turbine that produces electric energy.

Erosion the wearing away of the land surface by wind, water, ice or other geologic agents. Erosion occurs naturally from weather or runoff, but is often intensified by human land use practices.

Eutrophication the process of enrichment of water bodies by nutrients. Eutrophication of a lake normally contributes to its slow evolution into a bog or marsh and ultimately to dry land. Eutrophication may be accelerated by human activities, thereby speeding up the aging process.

Evaporation the process by which water becomes a vapor at a temperature below the boiling point.

Facultative organisms that can survive and function in the presence or absence of free, elemental oxygen.

Fecal coliform the portion of the coliform bacteria group that is present in the intestinal tracts and feces of warm-blooded animals.

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Field capacity the capacity of soil to hold water. It is measured as the ratio of the weight of water retained by the soil to the weight of the dry soil.

Filtration the mechanical process that removes particulate matter by separating water from solid material, usually by passing it through sand.

Floc solids that join to form larger particles that will settle better.

Flocculation slow mixing process in which particles are brought into contact with the intent of promoting their agglomeration.

Flume a flow rate measurement device.

Fluoridation chemical addition to water to reduce incidence of dental caries in children.

Food-to-microorganisms ratio (F/M) an activated sludge process control calculation based upon the amount of food (BOD_5 or COD) available per pound of mixed liquor volatile suspended solids.

Force main a pipe that carries wastewater under pressure from the discharge side of a pump to a point of gravity flow downstream.

Grab sample an individual sample collected at a randomly selected time.

Graywater water that has been used for showering, clothes washing, and faucet uses. Kitchen sink and toilet water is excluded. This water has excellent potential for reuse as irrigation for yards.

Grit heavy inorganic solids, such as sand, gravel, eggshells, or metal filings.

Groundwater the supply of fresh water found beneath the earth's surface (usually in aquifers) often used for supplying wells and springs. Because groundwater is a major source of drinking water, concern is growing over areas where leaching agricultural or industrial pollutants or substances from leaking underground storage tanks (USTs) are contaminating groundwater.

Groundwater hydrology the branch of hydrology that deals with groundwater. It consists of its occurrence and movements, its replenishment and depletion, the properties of rocks that control groundwater movement and storage, and the methods of investigation and use of groundwater.

Groundwater recharge the inflow to a groundwater reservoir.

Groundwater runoff a portion of runoff that has passed into the ground, has become groundwater, and has been discharged into a stream channel as spring or seepage water.

Hardness the concentration of calcium and magnesium salts in water.

Headloss amount of energy used by water in moving from one point to another.

Heavy metals metallic elements with high atomic weights (e.g., mercury, chromium, cadmium, arsenic, and lead). They can damage living things at low concentrations and tend to accumulate in the food chain.

Holding pond a small basin or pond designed to hold sediment laden or contaminated water until it can be treated to meet water quality standards or used in some other way.

Hydraulic cleaning cleaning pipe with water under enough pressure to produce high water velocities.

Hydraulic gradient a measure of the change in groundwater head over a given distance.

Hydraulic head the height above a specific datum (generally sea level) that water will rise in a well.

Hydrologic cycle (water cycle) the cycle of water movement from the atmosphere to the earth and back to the atmosphere through various processes. These processes include: precipitation, infiltration, percolation, storage, evaporation, transpiration and condensation.

Hydrology the science dealing with the properties, distribution, and circulation of water.

Impoundment a body of water, such as a pond, confined by a dam, dike, floodgate, or other barrier, that is used to collect and store water for future use.

Industrial wastewater wastes associated with industrial manufacturing processes.

Infiltration the gradual downward flow of water from the surface into soil material.

Infiltration/inflow extraneous flows in sewers; simply, inflow is water discharged into sewer pipes or service connections from such sources as foundation drains, roof leaders, cellar and yard area drains, cooling water from air conditioners, and other clean-water discharges from commercial and industrial establishments. Defined by Metcalf & Eddy as follows:[2]

- **Infiltration** water entering the collection system through cracks, joints, or breaks.
- **Steady inflow** water discharged from cellar and foundation drains, cooling water discharges, and drains from springs and swampy areas. This type of inflow is steady and is identified and measured along with infiltration.
- **Direct flow** those types of inflow that have a direct stormwater runoff connection to the sanitary sewer and cause an almost immediate increase in wastewater flows. Possible sources are roof leaders, yard and areaway

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drains, manhole covers, cross connections from storm drains and catch basins, and combined sewers.

- **Total inflow** the sum of the direct inflow at any point in the system plus any flow discharged from the system upstream through overflows, pumping station bypasses, and the like.
- **Delayed inflow** stormwater that may require several days or more to drain through the sewer system. This category can include the discharge of sump pumps from cellar drainage as well as the slowed entry of surface water through manholes in ponded areas.

Influent wastewater entering a tank, channel, or treatment process.

Inorganic chemical/compounds chemical substances of mineral origin, not of carbon structure. These include metals such as lead, iron (ferric chloride), and cadmium.

Ion exchange process a process used to remove hardness from water.

Jar Test laboratory procedure used to estimate proper coagulant dosage.

Langelier saturation index (L.I.) a numerical index that indicates whether calcium carbonate will be deposited or dissolved in a distribution system.

Leaching the process by which soluble materials in the soil, such as nutrients, pesticide chemicals or contaminants, are washed into a lower layer of soil or are dissolved and carried away by water.

License a certificate issued by the State Board of Waterworks/Wastewater Works Operators authorizing the holder to perform the duties of a wastewater treatment plant operator.

Lift station a wastewater pumping station designed to "lift" the wastewater to a higher elevation. A lift station normally employs pumps or other mechanical devices to pump the wastewater and discharges into a pressure pipe called a force main.

Maximum contaminant level (MCL) an enforceable standard for protection of human health.

Mean cell residence time (MCRT) the average length of time mixed liquor suspended solids particle remains in the activated sludge process. May also be known as sludge retention time.

Mechanical cleaning clearing pipe by using equipment (bucket machines, power rodders, or hand rods) that scrapes, cuts, pulls, or pushes the material out of the pipe.

Membrane process a process that draws a measured volume of water through a filter membrane with small enough openings to take out contaminants.

Metering pump a chemical solution feed pump that adds a measured amount of solution with each stroke or rotation of the pump.

Mixed liquor the suspended solids concentration of the mixed liquor.

Mixed liquor volatile suspended solids (MLVSS) the concentration of organic matter in the mixed liquor suspended solids.

Milligrams/liter (mg/L) a measure of concentration equivalent to parts per million.

National Pollutant Discharge Elimination System permit a permit that authorizes the discharge of treated wastes and specifies the conditions that must be met for discharge.

Nephelometric turbidity unit (NTU) a unit that indicates the amount of turbidity in a water sample.

Nitrogenous oxygen demand (NOD) a measure of the amount of oxygen required to biologically oxidize nitrogen compounds under specified conditions of time and temperature.

Nonpoint Source (NPS) Pollution forms of pollution caused by sediment, nutrients, organic and toxic substances originating from land use activities that are carried to lakes and streams by surface runoff. Nonpoint source pollution occurs when the rate of materials entering these water bodies exceeds natural levels.

Nutrients substances required to support living organisms. Usually refers to nitrogen, phosphorus, iron, and other trace metals.

Organic chemicals/compounds animal or plant-produced substances containing mainly carbon, hydrogen, and oxygen, such as benzene and toluene.

Parts per million (ppm) the number of parts by weight of a substance per million parts of water. This unit is commonly used to represent pollutant concentrations. Large concentrations are expressed in percentages.

Pathogenic disease causing. A pathogenic organism is capable of causing illness.

Percolation the movement of water through the subsurface soil layers, usually continuing downward to the groundwater or water table reservoirs.

pH a way of expressing both acidity and alkalinity on a scale of 0 to 14, with 7 representing neutrality; numbers less than 7 indicate increasing acidity and numbers greater than 7 indicate increasing alkalinity.

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Photosynthesis a process in green plants in which water, carbon dioxide, and sunlight combine to form sugar.

Piezometric surface an imaginary surface that coincides with the hydrostatic pressure level of water in an aquifer.

Point source pollution a type of water pollution resulting from discharges into receiving waters from easily identifiable points. Common point sources of pollution are discharges from factories and municipal sewage treatment plants.

Pollution the alteration of the physical, thermal, chemical, or biological quality of, or the contamination of, any water in the state that renders the water harmful, detrimental, or injurious to humans, animal life, vegetation, property, public health, safety, or welfare, or impairs the usefulness or the public enjoyment of the water for any lawful or reasonable purpose.

Porosity that part of a rock that contains pore spaces without regard to size, shape, interconnection, or arrangement of openings. It is expressed as percentage of total volume occupied by spaces.

Potable water water satisfactorily safe for drinking purposes from the standpoint of its chemical, physical, and biological characteristics.

Precipitate a deposit on the earth of hail, rain, mist, sleet, or snow. The common process by which atmospheric water becomes surface or subsurface water, the term precipitation is also commonly used to designate the quantity of water precipitated.

Preventive maintenance (PM) regularly scheduled servicing of machinery or other equipment using appropriate tools, tests, and lubricants. This type of maintenance can prolong the useful life of equipment and machinery and increase its efficiency by detecting and correcting problems before they cause a breakdown of the equipment.

Purveyor an agency or person that supplies potable water.

Radon a radioactive, colorless, odorless gas that occurs naturally in the earth. When trapped in buildings, concentrations build up and can cause health hazards such as lung cancer.

Recharge the addition of water into a groundwater system.

Reservoir a pond, lake, tank, or basin (natural or human made) where water is collected and used for storage. Large bodies of groundwater are called groundwater reservoirs; water behind a dam is also called a reservoir of water.

Reverse osmosis a process in which almost pure water is passed through a semipermeable membrane.

Return activated sludge solids (RASS) the concentration of suspended solids in the sludge flow being returned from the settling tank to the head of the aeration tank.

River basin a term used to designate the area drained by a river and its tributaries.

Sanitary wastewater wastes discharged from residences and from commercial, institutional, and similar facilities that include both sewage and industrial wastes.

Schmutzdecke layer of solids and biological growth that forms on top of a slow sand filter, allowing the filter to remove turbidity effectively without chemical coagulation.

Scum the mixture of floatable solids and water removed from the surface of the settling tank.

Sediment transported and deposited particles derived from rocks, soil, or biological material.

Sedimentation a process that reduces the velocity of water in basins so that suspended material can settle out by gravity.

Seepage the appearance and disappearance of water at the ground surface. Seepage designates movement of water in saturated material. It differs from percolation, which is predominantly the movement of water in unsaturated material.

Septic tanks used to hold domestic wastes when a sewer line is not available to carry them to a treatment plant. The wastes are piped to underground tanks directly from a home or homes. Bacteria in the wastes decompose some of the organic matter, the sludge settles on the bottom of the tank, and the effluent flows out of the tank into the ground through drains.

Settleability a process control test used to evaluate the settling characteristics of the activated sludge. Readings taken at 30 to 60 min are used to calculate the settled sludge volume (SSV) and the sludge volume index (SVI).

Settled sludge volume (SSV) the volume (in percent) occupied by an activated sludge sample after 30 to 60 minutes of settling. Normally written as SSV with a subscript to indicate the time of the reading used for calculation (SSV_{60} or SSV_{30}).

Sludge the mixture of settleable solids and water removed from the bottom of the settling tank.

Sludge retention time (SRT) see mean cell residence time.

Sludge volume index (SVI) a process control calculation used to evaluate the settling quality of the activated sludge. Requires the SSV_{30} and mixed liquor suspended solids test results to calculate.

Soil moisture (soil water) water diffused in the soil. It is found in the upper part of the zone of

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aeration from which water is discharged by transpiration from plants or by soil evaporation.

Specific heat the heat capacity of a material per unit mass. The amount of heat (in calories) required to raise the temperature of 1 g of a substance 1°C; the specific heat of water is 1 cal.

Storm sewer a collection system designed to carry only stormwater runoff.

Stormwater runoff resulting from rainfall and snowmelt.

Stream a general term for a body of flowing water. In hydrology, the term is generally applied to the water flowing in a natural channel as distinct from a canal. More generally, it is applied to the water flowing in any channel, natural or artificial. Some types of streams include: (1) Ephemeral: a stream that flows only in direct response to precipitation, and whose channel is at all times above the water table; (2) Intermittent or Seasonal: a stream that flows only at certain times of the year when it receives water from springs, rainfall, or from surface sources such as melting snow; (3) Perennial: a stream that flows continuously; (4) Gaining: a stream or reach of a stream that receives water from the zone of saturation. It is an effluent stream; (5) Insulated: a stream or reach of a stream that neither contributes water to the zone of saturation nor receives water from it. It is separated from the zones of saturation by an impermeable bed; (6) Losing: a stream or reach of a stream that contributes water to the zone of saturation. An influent stream; (7) Perched: a perched stream is either a losing stream or an insulated stream that is separated from the underlying groundwater by a zone of aeration.

Supernatant the liquid standing above a sediment or precipitate.

Surface water lakes, bays, ponds, impounding reservoirs, springs, rivers, streams, creeks, estuaries, wetlands, marshes, inlets, canals, gulfs inside the territorial limits of the state, and all other bodies of surface water, natural or artificial, inland or coastal, fresh or salt, navigable or nonnavigable, and including the beds and banks of all watercourses and bodies of surface water, that are wholly or partially inside or bordering the state or subject to the jurisdiction of the state; except that waters in treatment systems that are authorized by state or federal law, regulation, or permit, and that are created for the purpose of water treatment are not considered to be waters in the state.

Surface tension the free energy produced in a liquid surface by the unbalanced inward pull exerted by molecules underlying the layer of surface molecules.

Thermal pollution the degradation of water quality by the introduction of a heated effluent. Primarily the result of the discharge of cooling waters from industrial processes (particularly from electrical power generation), waste heat eventually results from virtually every energy conversion.

Titrant a solution of known strength of concentration; used in titration.

Titration a process whereby a solution of known strength (titrant) is added to a certain volume of treated sample containing an indicator. A color change shows when the reaction is complete.

Titrator an instrument (usually a calibrated cylinder (tube-form)) used in titration to measure the amount of titrant being added to the sample.

Total dissolved solids the amount of material (inorganic salts and small amounts of organic material) dissolved in water and commonly expressed as a concentration in terms of milligrams per liter.

Total suspended solids (TSS) total suspended solids in water, commonly expressed as a concentration in terms of milligrams per liter.

Toxicity the occurrence of lethal or sublethal adverse affects on representative sensitive organisms due to exposure to toxic materials. Adverse effects caused by conditions of temperature, dissolved oxygen, or nontoxic dissolved substances are excluded from the definition of toxicity.

Transpiration the process by which water vapor escapes from the living plant, principally the leaves, and enters the atmosphere.

Vaporization the change of a substance from a liquid or solid state to a gaseous state.

Volatile Organic Compound (VOC) any organic compound that participates in atmospheric photochemical reactions except for those designated by the EPA administrator as having negligible photochemical reactivity.

Wastewater the water supply of a community after it has been soiled by use.

Waste activated sludge solids (WASS) the concentration of suspended solids in the sludge being removed from the activated sludge process.

Water cycle the process by which water travels in a sequence from the air (condensation) to the earth (precipitation) and returns to the atmosphere (evaporation). It is also referred to as the hydrologic cycle.

Water quality standard a plan for water quality management containing four major elements: water use, criteria to protect uses, implementation plans, and enforcement plans. An antidegradation

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statement is sometimes prepared to protect existing high quality waters.

Water quality a term used to describe the chemical, physical, and biological characteristics of water with respect to its suitability for a particular use.

Water supply any quantity of available water.

Waterborne disease a disease caused by a microorganism that is carried from one person or animal to another by water.

Watershed the area of land that contributes surface runoff to a given point in a drainage system.

Weir a device used to measure wastewater flow.

Zone of aeration a region in the earth above the water table. Water in the zone of aeration is under atmospheric pressure and would not flow into a well.

Zoogleal slime the biological slime that forms on fixed film treatment devices. It contains a wide variety of organisms essential to the treatment process.

3.4 CHAPTER REVIEW QUESTIONS AND PROBLEMS

3.1. Matching exercise: Match the definitions listed in part A with the terms listed in Part B by placing the correct letter in the blank. After completing this exercise, check your answers with those provided in Appendix A.

Part A	Part B
1. A nonchemical turbidity removal layer in a slow sand filter. _____	a. pH
2. Region in earth (soil) above the water table. _____	b. algae bloom
3. Compound associated with photochemical reaction. _____	c. zone of aeration
4. Oxygen used in water rich inorganic matter. _____	d. hydrological cycle
5. A stream that receives water from the zone of saturation. _____	e. point source pollution
6. The addition of water into a groundwater system. _____	f. perennial
7. The natural water cycle. _____	g. organic
8. Present in intestinal tracts and feces of animals and humans. _____	h. connate water
9. Discharge from a factory or municipal sewage treatment plant. _____	i. fecal coliform
10. Common to fixed film treatment devices. _____	j. BOD
11. Identified water that is safe to drink. _____	k. field capacity
12. The capacity of soil to hold water. _____	l. transpiration
13. Used to measure acidity and alkalinity. _____	m. biota
14. Rain mixed with sulfur oxides. _____	n. specific heat
15. Enrichment of water bodies by nutrients. _____	o. Schmutzdecke
16. A solution of known strength of concentration. _____	p. recharge
17. Water lost by foliage. _____	q. Zoogleal slime
18. Another name for a wastewater pumping station. _____	r. eutrophication
19. Plants and animals indigenous to an area. _____	s. gaining
20. The amount of oxygen dissolved in water. _____	t. VOC
21. A stream that flows continuously. _____	u. potable
22. A result of excessive nutrients within a water body. _____	v. acid rain
23. Change in groundwater head over a given distance. _____	w. titrant
24. Water trapped in sedimentary rocks. _____	x. lift station
25. Heat capacity of a material per unit mass. _____	y. DO
26. A compound derived from material that once lived. _____	z. hydraulic gradient

REFERENCES

1. Pielou, E.C., *Fresh Water*, University of Chicago, Chicago, 1998, preface.
2. Metcalf & Eddy, Inc. *Wastewater Engineering: Treatment, Disposal, Reuse*, 3rd ed., Tchobanoglous, G. (Ed.), McGraw-Hill, New York, 1991, pp. 29–31.

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PART II

Water/Wastewater Operations: Math and Technical Aspects

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4 Water and Wastewater Math Operations

To operate a waterworks and/or a wastewater treatment plant, and to pass the examination for an operator's license, you must know how to perform certain mathematical operations. However, do not panic, as Price points out, "Those who have difficulty in math often do not lack the ability for mathematical calculation, they merely have not learned, or have not been taught, the 'language of math."[1]

4.1 INTRODUCTION

Without the ability to perform mathematical calculations, operators would have difficulty in properly operating water and wastewater systems. In reality, most of the calculations operators need to perform are not difficult. Generally, math ability through basic algebra is all that is needed. Experience has shown that skill with math operations used in water and wastewater system operations is an acquired skill that is enhanced and strengthened with practice.

Note: Keep in mind that mathematics is a language — a universal language. Mathematical symbols have the same meaning to people speaking many different languages throughout the globe. The key to learning mathematics is to learn the language — the symbols, definitions and terms, of mathematics that allow you to understand the concepts necessary to perform the operations.

In this chapter, we assume the reader is well grounded in basic math principles. We do not cover basic operations such as addition, subtraction, multiplication, and division. However, we do include, for review purposes, a few basic math calculations in the Chapter Review Questions/Problems at the end of the chapter.

4.2 CALCULATION STEPS

As with all math operations, many methods can be successfully used to solve water and wastewater system problems. We provide one of the standard methods of problem solving in the following:

1. If appropriate, make a drawing of the information in the problem.
2. Place the given data on the drawing.
3. Determine what the question is. This is the first thing you should determine as you begin to solve the problem, along with, "What are they really looking for?" Writing down exactly what is being looked for is always smart. Sometimes the answer has more than one unknown. For instance, you may need to find X and then find Y.
4. If the calculation calls for an equation, write it down.
5. Fill in the data in the equation and look to see what is missing.
6. Rearrange or transpose the equation, if necessary.
7. If available, use a calculator.
8. Always write down the answer.
9. Check any solution obtained.

4.3 TABLE OF EQUIVALENTS, FORMULAE, AND SYMBOLS

In order to work mathematical operations to solve problems (for practical application or for taking licensure examinations), it is essential to understand the language, equivalents, symbols, and terminology used.

Because this handbook is designed for use in practical on-the-job applications, equivalents, formulae, and symbols are included, as a ready reference, in Table 4.1.

4.4 TYPICAL WATER AND WASTEWATER MATH OPERATIONS

4.4.1 Arithmetic Average (or Arithmetic Mean) and Median

During the day-to-day operation of a wastewater treatment plant, considerable mathematical data are collected. The data, if properly evaluated, can provide useful information for trend analysis and indicate how well the plant or unit process is operating. However, because there may be much variation in the data, it is often difficult to determine trends in performance.

Arithmetic average refers to a statistical calculation used to describe a series of numbers such as test results. By calculating an average, a group of data is represented by a single number. This number may be considered typical of the group. The arithmetic mean is the most commonly used measurement of average value.

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TABLE 4.1
Equivalents, Formulae, and Symbols

Equivalents

12 in.	= 1 ft
36 in.	= 1 yd
144 in.^{2}	= 1 ft^2
9 ft^2	= 1 yd^2
43,560 ft^2	= 1 ac
1 ft^3	= 1728 in.^{3}
1 ft^3 H_20	= 7.48 gal
1 ft^3 H_20	= 62.4 lb
1 gal of H_20	= 8.34 lb
1 L	= 1.000 mL
1 g	= 1.000 mg
1 MGD (million gal[MG]/d)	= 694 gal/min, 1.545 ft^3/sec
average BOD/capita/day	= .17 lb
average SS/capita/day	= .20
average daily flow	= assume 100 gal/capita/day

Symbols

A	= Area
V	= Velocity
t	= Time
SVI	= Sludge Volume Index
v	= Volume
#	= Pounds
eff	= Effluent
W	= Width
D	= Depth
L	= Length
H	= Height
Q	= Flow
C	= Circumference
r	= Radius
π	= pi (3.14)
WAS	= Waste activated sludge
RAS	= Return activated sludge
MLSS	= Mixed liquor suspended solids
MLVSS	= Mixed liquor volatile suspended solids

Formulae

$$\text{SVI} = \frac{\text{v}}{\text{Concentration}} \times 100$$

$$\text{Q} = \text{A} \times \text{V}$$

Detention time = v/Q

$$\text{v} = \text{L} \times \text{W} \times \text{D}$$

$$\text{area} = \text{W} \times \text{L}$$

$$\text{Circular area} = \pi \times \text{Diameter}^2$$

$$\text{C} = \pi\text{d}$$

Hydraulic loading rate = Q/A

$$\text{Sludge age} = \frac{\#\,\text{MLSS in aeration tank}}{\#\,\text{SS in primary eff/d}}$$

$$\text{Mean cell residence time} = \frac{\#\,\text{SS in secondary system (aeration tank + sec. clarifier)}}{\#\,\text{WAS/d} + \text{SS in eff/d}}$$

$$\text{Organic loading rate} = \frac{\#\,\text{BOD/d}}{\text{v}}$$

Source: From Spellman, F.R., *Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.

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Note: When evaluating information based on averages, remember that the average reflects the general nature of the group and does not necessarily reflect any one element of that group.

Arithmetic average is calculated by dividing the sum of all of the available data points (test results) by the number of test results:

$$\frac{\text{Test 1} + \text{Test 2} + \text{Test 3} + \cdots + \text{Test N}}{\text{Number of Tests Performed (N)}} \quad (4.1)$$

EXAMPLE 4.1

Problem:

Effluent biochemical oxygen demand (BOD) test results for the treatment plant during the month of September are shown below:

Test 1	20 mg/L
Test 2	31 mg/L
Test 3	22 mg/L
Test 4	15 mg/L

What is the average effluent BOD for the month of September?

Solution:

$$\text{Average} = \frac{20\ \text{mg/L} + 31\ \text{mg/L} + 22\ \text{mg/L} + 15\ \text{mg/L}}{4}$$

$$= 22\ \text{mg/L}$$

EXAMPLE 4.2

Problem:

For the primary influent flow, the following composite-sampled solids concentrations were recorded for the week:

Monday	300 mg/L SS
Tuesday	312 mg/L SS
Wednesday	315 mg/L SS
Thursday	320 mg/L SS
Friday	311 mg/L SS
Saturday	320 mg/L SS
Sunday	310 mg/L SS
Total	2188 mg/L SS

Solution:

$$\text{Average SS} = \frac{\text{Sum of All Measurements}}{\text{Number of Measurements Used}}$$

$$= \frac{2188\ \text{mg/L SS}}{7}$$

$$= 312.6\ \text{mg/L SS}$$

EXAMPLE 4.3

Problem:

A waterworks operator takes a chlorine residual measurement every day. We show part of the operating log in Table 4.2.

TABLE 4.2
Daily Chlorine Residual Results

Day	Chlorine Residual (mg/L)
Monday	0.9
Tuesday	1.0
Wednesday	1.2
Thursday	1.3
Friday	1.4
Saturday	1.1
Sunday	0.9

Source: From Spellman, F.R., *Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.

Find the mean.

Solution:

Add up the seven chlorine residual readings: 0.9 + 1.0 + 1.2 + 1.3 + 1.4 + 1.1 + 0.9 = 7.8. Next, divide by the number of measurements (in this case 7): 7.8 ÷ 7 = 1.11. The mean chlorine residual for the week was 1.11 mg/L.

Definition: The median is defined as the value of the central item when the data are arrayed by size. First, arrange all of the readings in either ascending or descending order. Then find the middle value.

EXAMPLE 4.4

Problem:

In our chlorine residual example, what is the median?

Solution:

Arrange the values in ascending order:

0.9, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4

The middle value is the fourth one — 1.1. Therefore, the median chlorine residual is 1.1 mg/L. (Usually, the median will be a different value than the mean.)

If the data contain an even number of values, you must add one more step, since no middle value is present. You must find the two values in the middle, and then find the mean of those two values.

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EXAMPLE 4.5

Problem:

A water system has four wells with the following capacities: 115, 100, 125, and 90 gal/min. What are the mean and the median pumping capacities?

Solution:

The mean is:

$$\frac{115\ \text{gal/min} + 100\ \text{gal/min} + 125\ \text{gal/min} + 90\ \text{gal/min}}{4} =$$

$$107.5\ \text{gal/min}$$

To find the median, arrange the values in order:

90 gal/min, 100 gal/min, 115 gal/min, 125 gal/min

With four values, there is no single middle value, so we must take the mean of the two middle values:

$$\frac{100\ \text{gpm} + 115\ \text{gpm}}{2} = 107.5\ \text{gpm}$$

Note: At times, determining what the original numbers were like is difficult (if not impossible) when dealing only with averages.

EXAMPLE 4.6

Problem:

A water system has four storage tanks. Three of them have a capacity of 100,000 gal each, while the fourth has a capacity of 1 million gallons (MG). What is the mean capacity of the storage tanks?

Solution:

The mean capacity of the storage tanks is:

$$\frac{100{,}000 + 100{,}000 + 100{,}000 + 1{,}000{,}000}{4} = 325{,}000\ \text{gal}$$

Note: Notice that no tank in Example 4.6 has a capacity anywhere close to the mean. The median capacity requires us to take the mean of the two middle values; since they are both 100,000 gal, the median is 100,000 gal. Although three of the tanks have the same capacity as the median, these data offer no indication that one of these tanks holds 1 million gal — information that could be important for the operator to know.

4.4.2 RATIO

Recall that a ratio is the comparison of two numbers by division or an indicated division. A ratio is usually stated in the form A is to B as C is to D, and is written as two fractions that are equal to each other:

$$\frac{A}{B} = \frac{C}{D} \tag{4.2}$$

We solve ratio problems by cross-multiplying; we multiply the left numerator (A) by the right denominator (D) and say that A is equal to the left denominator (B) times the right numerator (C):

$$A \times D = B \times C$$

$$AD = BC \tag{4.3}$$

If one of the four items is unknown, we solve the ratio by dividing the two known items that are multiplied together by the known item that is multiplied by the unknown. This is best shown by a couple of examples:

EXAMPLE 4.7

Problem:

If we need 4 lb of alum to treat 1000 gal of H_2O, how many pounds of alum will we need to treat 12,000 gallons?

Solution:

We state this as a ratio: 4 lb of alum is to 1000 gallons of H_2O as pounds of alum (or x) is to 12,000 gal. We set this up this way:

$$\frac{4\ \text{lb alum}}{1000\ \text{gal}\ H_2O} = \frac{x\ \text{lb alum}}{12{,}000\ \text{gal}\ H_2O}$$

Cross-multiplying:

$$1000 \times x = 4 \times 12{,}000$$

$$x = \frac{4 \times 12{,}000}{1000}$$

$$x = 48\ \text{lb alum}$$

EXAMPLE 4.8

Problem:

If 10 gal of fuel oil costs $5.25, how much does 18 gal cost?

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$$\frac{10\text{ gal}}{\$5.25} = \frac{18\text{ gal}}{\$y}$$

$$10 \times y = 18 \times \$5.25$$

$$y = \frac{18 \times \$5.25}{10}$$

$$y = \frac{94.5}{10}$$

$$y = \$9.45$$

4.4.3 Percent

Percent (like fractions) is another way of expressing a part of a whole. The term percent means per hundred, so a percentage is the number out of 100. For example, 22% means 22 out of 100, or if we divide 22 by 100, we get the decimal 0.22:

$$22\% = \frac{22}{100} = 0.22$$

4.4.3.1 Practical Percentage Calculations

Percentage is often designated by the symbol %. Thus, 10% means 10 percent, 10/100, or 0.10. These equivalents may be written in the reverse order: 0.10 = 10/100 = 10%. In water and wastewater treatment, percent is frequently used to express plant performance and for control of sludge treatment processes.

Note: To determine percent divide the quantity you wish to express as a percent by the total quantity then multiply by 100.

$$\text{Percent} = \frac{\text{Quantity} \times 100}{\text{Total}} \tag{4.4}$$

Example 4.9

Problem:

The plant operator removes 6000 gal of sludge from the settling tank. The sludge contains 320 gal of solids. What is the percent of solids in the sludge?

Solution:

$$\text{Percent} = \frac{320\text{ gal}}{6000\text{ gal}} \times 100$$

$$= 5.3\%$$

Example 4.10

Problem:

Sludge contains 5.3% solids. What is the concentration of solids in decimal percent?

Solution:

$$\text{Decimal Percent} = \frac{5.3\%}{100} = 0.053$$

Note: Unless otherwise noted all calculations in the handbook using percent values require the percent be converted to a decimal before use.

Note: To determine what quantity a percent equals first convert the percent to a decimal then multiply by the total quantity.

$$\text{Quantity} = \text{Total} \times \text{Decimal Percent} \tag{4.5}$$

Example 4.11

Problem:

Sludge drawn from the settling tank is 8% solids. If 2400 gal of sludge are withdrawn, how many gallons of solids are removed?

Solution:

$$\text{gallons} = \frac{8\%}{100} \times 2400\text{ gal} = 192\text{ gal}$$

Example 4.12

Problem:

Calcium hypochlorite (HTH) contains 65% available chlorine. What is the decimal equivalent of 65%?

Solution:

Since 65% means 65 per hundred, divide 65 by 100 (65/100), which is 0.65.

Example 4.13

Problem:

If a 50-ft high water tank has 32 ft of water in it, how full is the tank in terms of the percentage of its capacity?

Solution:

$$\frac{32\text{ ft}}{50\text{ ft}} = 0.64\ (\text{decimal equivalent})$$

$$0.64 \times 100 = 64\%$$

Thus, the tank is 64% full.

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4.4.4 Units and Conversions

Most of the calculations made in the water and wastewater operations involve using units. While the number tells us how many, the units tell us what we have. Examples of units include: inches, feet, square feet, cubic feet, gallons, pounds, milliliters, milligrams per liter, pounds per square inch, miles per hour, and so on.

Conversions are a process of changing the units of a number to make the number usable in a specific instance. Multiplying or dividing into another number to change the units of the number accomplishes conversions. Common conversions in water and wastewater operations are:

1. Gallons per minute to cubic feet per second
2. Million gallons to acre-feet
3. Cubic foot per second to acre-feet
4. Cubic foot per second of water to weight
5. Cubic foot of H_2O to gallons
6. Gallons of water to weight
7. Gallons per minute to million gallons per day
8. Pounds to feet of head (the measure of the pressure of water expressed as height of water in feet — 1 psi = 2.31 feet of head)

In many instances, the conversion factor cannot be derived — it must be known. Therefore, we use tables such as the one below (Table 4.3) to determine the common conversions.

Note: Conversion factors are used to change measurements or calculated values from one unit of measure to another. In making the conversion from one unit to another, you must know two things: (1) the exact number that relates the two units, and (2) whether to multiply or divide by that number

Most operators memorize some standard conversions. This happens because of using the conversions, not because of attempting to memorize them.

4.4.4.1 Temperature Conversions

An example of a type of conversion typical in water and wastewater operations is provided in this section on temperature conversions.

Note: Operators should keep in mind that temperature conversions are only a small part of the many conversions that must be made in real world systems operations.

Most water and wastewater operators are familiar with the formulas used for Fahrenheit and Celsius temperature conversions:

TABLE 4.3
Common Conversions

Linear Measurements
1 in. = 2.54 cm
1 ft = 30.5 cm
1 m = 100 cm = 3.281 ft = 39.4 in.
1 ac = 43,560 ft^2
1 yd = 3 ft
Volume
1 gal = 3.78 L
1 ft^3 = 7.48 gal
1 L = 1000 mL
1 ac-ft = 43,560 ft^3
1 gal = 32 cups
1 lb = 16 oz dry wt.
Weight
1 ft^3 of water = 62.4 lb
1 gal = 8.34 lb
1 lb = 453.6 g
1 kg = 1000 g = 2.2 lb
1% = 10,000 mg/L
Pressure
1 ft of head = 0.433 psi
1 psi = 2.31 ft of head
Flow
1 ft^3/sec = 448 gal/min
1 gal/min = 1440 gal/d

Source: From Spellman, F.R., *Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.

$$°C = 5/9(°F - 32°) \tag{4.6}$$

$$°F = 5/9(°C + 32°) \tag{4.7}$$

These conversions are not difficult to perform. The difficulty arises when we must recall these formulas from memory.

Probably the easiest way to recall these important formulas is to remember three basic steps for both Fahrenheit and Celsius conversions:

1. Add 40°.
2. Multiply by the appropriate fraction (5/9 or 9/5).
3. Subtract 40°.

Obviously, the only variable in this method is the choice of 5/9 or 9/5 in the multiplication step. To make the proper choice, you must be familiar with two scales. On the Fahrenheit scale, the freezing point of water is 32°, and 0° on the Celsius scale. The boiling point of water is 212° on the Fahrenheit scale and 100° on the Celsius scale.

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What does this mean? Why is it important?

Note, for example, that at the same temperature, higher numbers are associated with the Fahrenheit scale and lower numbers with the Celsius scale. This important relationship helps you decide whether to multiply by 5/9 or 9/5. Let us look at a few conversion problems to see how the three-step process works.

EXAMPLE 4.14

Problem:

Convert 220°F to Celsius.

Solution:

Using the three-step process, we proceed as follows:

Step 1: Add 40°F:

$$220°F + 40°F = 260°F$$

Step 2: 260°F must be multiplied by either 5/9 or 9/5. Since the conversion is to the Celsius scale, you will be moving to number smaller than 260. Through reason and observation, obviously we see that multiplying 260 by 9/5 would almost be the same as multiplying by 2, which would double 260, rather than make it smaller. On the other hand, multiplying by 5/9 is about the same as multiplying by 1/2, which would cut 260 in half. Because we wish to move to a smaller number, we should multiply by 5/9:

$$5/9 \times 260°F = 144.4°C$$

Step 3: Now subtract 40°:

$$144.4°C \times 40°C = 104.4°C$$

Therefore, 220°F = 104.4°C

EXAMPLE 4.15

Problem:

Convert 22°C to Fahrenheit.

Step 1: Add 40°F:

$$22°F + 40°F = 62°F$$

Step 2: Because we are converting from Celsius to Fahrenheit, we are moving from a smaller to larger number, and should use 9/5 in the multiplication:

$$9/5 \times 62°F = 112°F$$

Step 3: Subtract 40°:

$$112°F - 40°F = 72°F$$

Thus, 22°C = 72°F

Obviously, knowing how to make these temperature conversion calculations is useful. However, in practical (real world) operations, you may wish to use a temperature conversion table.

4.4.4.2 Milligrams per Liter (Parts per Million)

One of the most common terms for concentration is milligrams per liter (mg/L). For example, if a mass of 15 mg of oxygen is dissolved in a volume of 1 L of water, the concentration of that solution is expressed simply as 15 mg/L.

Very dilute solutions are more conveniently expressed in terms of micrograms per liter (μg/L). For example, a concentration of 0.005 mg/L is preferably written as its equivalent, 5 μg/L. Since 1000 μg = 1 mg, simply move the decimal point three places to the right when converting from mg/L to μL. Move the decimal three places to the left when converting from μg/L, to mg/L. For example, a concentration of 1250 μ/L is equivalent to 1.25 mg/L.

One liter of water has a mass of 1 kg. But 1 kg is equivalent to 1000 g or 1,000,000 mg. Therefore, if we dissolve 1 mg of a substance in 1 L of H_2O, we can say that there is 1 mg of solute per 1 million mg of water, or in other words, 1 part per million (ppm).

Note: For comparative purposes, we like to say that 1 ppm is analogous to a full shot glass of water sitting in the bottom of a full standard swimming pool.

Neglecting the small change in the density of water as substances are dissolved in it, we can say that, in general, a concentration of 1 mg/L is equivalent to 1 ppm. Conversions are very simple; for example, a concentration of 18.5 mg/L is identical to 18.5 ppm.

The expression mg/L is preferred over ppm, just as the expression μg/L is preferred over its equivalent of parts per billion (ppb). However, both types of units are still used, and the waterworks/wastewater operator should be familiar with both.

4.5 MEASUREMENTS: AREAS AND VOLUMES

Water and wastewater operators are often required to calculate surface areas and volumes.

Area is a calculation of the surface of an object. For example, the length and the width of a water tank can be measured, but the surface area of the water in the tank must be calculated. An area is found by multiplying two length measurements, so the result is a square measurement. For example, when multiplying feet by feet, we get square feet, which is abbreviated ft^2. Volume is the calculation of the space inside a three-dimensional object, and is calculated by multiplying three length measurements,

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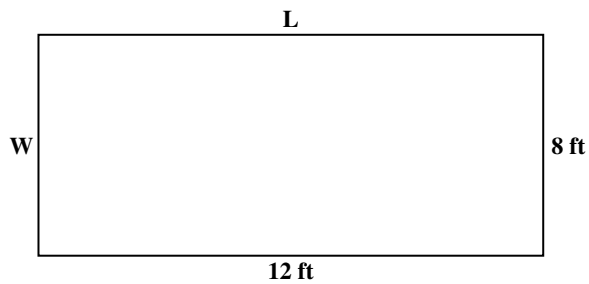

FIGURE 4.1 Rectangular shape showing calculation of surface area. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

or an area by a length measurement. The result is a cubic measurement, such as cubic feet (abbreviated ft^3).

4.5.1 Area of a Rectangle

The area of square or rectangular figures (such as the one shown in Figure 4.1) is calculated by multiplying the measurements of the sides.

$$A = L \times W \tag{4.8}$$

To determine the area of the rectangle shown in Figure 4.1, we proceed as follows:

$$A = L \times W$$

$$A = 12 \text{ ft} \times 8 \text{ ft}$$

$$A = 96 \text{ ft}^2$$

4.5.2 Area of a Circle

The diameter of a circle is the distance across the circle through its center, and is shown in calculations and on drawings by the letter D (see Figure 4.2). Half of the diameter — the distance from the center to the outside edge — is called the radius (r). The distance around the outside of the circle is called the circumference (C).

In calculating the area of a circle, the radius must be multiplied by itself (or the diameter by itself); this process is called squaring, and is indicated by the superscript number 2 following the item to be squared. For example, the radius squared is written as r^2, which indicates to multiply the radius by the radius.

When making calculations involving circular objects, a special number is required — referred to by the Greek letter pi (pronounced pie); the symbol for pi is π. Pi always has the value 3.1416.

The area of a circle is equal to the radius squared times the number pi.

$$A = \pi \times r^2 \tag{4.9}$$

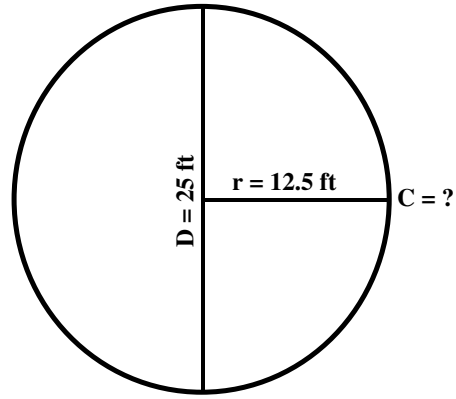

FIGURE 4.2 Circular shape showing diameter and radius. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Example 4.16

Problem:

Find the area of the circle shown in Figure 4.2.

Solution:

$$A = \pi \times r^2$$

$$A = \pi \times 12.5 \text{ ft} \times 12.5 \text{ ft}$$

$$A = 3.1416 \times 12.5 \text{ ft} \times 12.5 \text{ ft}$$

$$A = 490.9 \text{ ft}^2$$

At times, finding the diameter of a circular object is necessary, under circumstances that allow you to measure only the circumference (e.g., a pump shaft). The diameter and the circumference are related by the constant π:

$$C = \pi \times \text{Diameter or } \frac{C}{\pi} \tag{4.10}$$

4.5.3 Area of a Circular or Cylindrical Tank

If you were supervising a work team assigned to paint a water or chemical storage tank, you would need to know the surface area of the walls of the tank. To determine the tank's surface area, visualize the cylindrical walls as a rectangle wrapped around a circular base. The area of a rectangle is found by multiplying the length by the width; in this case, the width of the rectangle is the height of the wall and the length of the rectangle is the distance around the circle, the circumference.

The area of the sidewalls of a circular tank is found by multiplying the circumference of the base ($C = \pi \times$ Diameter) times the height of the wall (H):

$$A = \pi \times \text{Diameter} \times H \tag{4.11}$$

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For a tank with Diameter = 20 ft and H = 25 ft:

$$A = \pi \times D \times H$$

$$A = \pi \times 20 \text{ ft} \times 25 \text{ ft}$$

$$A = 3.1416 \times 20 \text{ ft} \times 25 \text{ ft}$$

$$A = 1570.8 \text{ ft}^2$$

To determine the amount of paint needed, remember to add the surface area of the top of the tank, which in this case we will say is 314 ft^2. Thus, the amount of paint needed must cover 1570.8 ft^2 + 314 ft^2 = 1884.8 or 1885 ft^2. If the tank floor should be painted, add another 314 ft^2.

4.5.4 Volume Calculations

4.5.4.1 Volume of Rectangular Tank

The volume of a rectangular object (such as a settling tank like the one shown in Figure 4.3) is calculated by multiplying together the length, the width, and the depth. To calculate the volume, you must remember that the length times the width is the surface area, which is then multiplied by the depth.

$$v = L \times W \times D \tag{4.12}$$

Example 4.17

Problem:

Using the dimensions given in Figure 4.3, determine the volume.

Solution:

$$v = L \times W \times D$$

$$v = A \times D$$

$$v = 12 \text{ ft} \times 6 \text{ ft} \times 6 \text{ ft}$$

$$v = 432 \text{ ft}^3$$

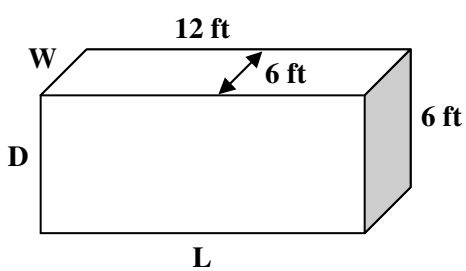

FIGURE 4.3 Rectangular settling tank illustrating calculation of volume. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

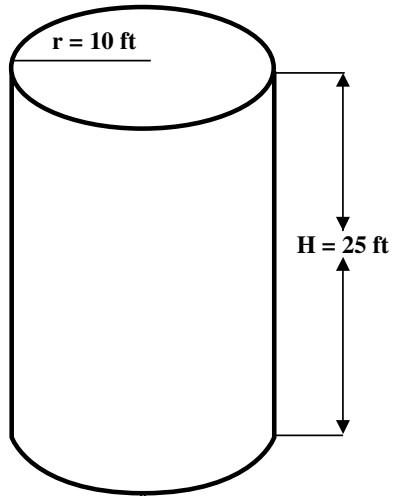

FIGURE 4.4 Circular or cylindrical water tank. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Note: For many calculations involving water, we need to know the volume of the tank in gallons rather than 1 ft^3 contains 7.48 gal.

4.5.4.2 Volume of a Circular or Cylindrical Tank

A circular tank consists of a circular floor surface with a cylinder rising above it (see Figure 4.4). The volume of a circular tank is calculated by multiplying the surface area times the height of the tank walls.

Example 4.18

Problem:

If a tank is 20 ft in diameter and 25 ft deep, how many gallons of water will it hold?

Solution:

In this type of problem, calculate the surface area first, multiply by the height and then convert to gallons.

$$r = \text{Diameter} \div 2 = 20 \text{ ft} \div 2 = 10 \text{ ft}$$

$$A = \pi \times r^2$$

$$A = \pi \times 10 \text{ ft} \times 10 \text{ ft}$$

$$A = 314 \text{ ft}^2$$

$$v = A \times H$$

$$v = 314 \text{ ft}^2 \times 25 \text{ ft}$$

$$v = 7850 \text{ ft}^3 \times 7.5 \text{ gal}/\text{ft}^3 = 58.875 \text{ gal}$$

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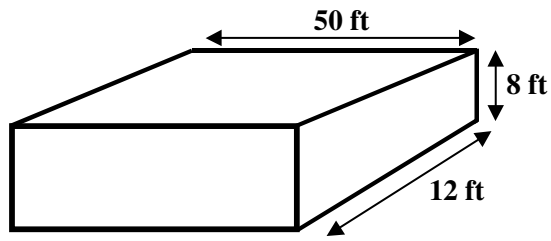

FIGURE 4.5 Rectangular tank. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

4.5.4.3 Example Volume Problems

EXAMPLE 4.19: TANK VOLUME (RECTANGULAR)

Problem:

Calculate the volume of the rectangular tank shown in Figure 4.5.

Note: If a drawing is not supplied with the problem, draw a rough picture or diagram. Make sure you label or identify the parts of the diagram from the information given in the question (see Figure 4.5).

Solution:

$$v\left(ft^3\right) = L \times W \times D$$

$$= 50\ ft \times 12\ ft \times 8\ ft$$

$$= 4800\ ft^3$$

EXAMPLE 4.20: TANK VOLUME (CIRCULAR)

Problem:

The diameter of a tank is 70 ft. When the water depth is 30 ft, what is the volume of wastewater in the tank in gallons?

Note: Draw a diagram similar to Figure 4.6.

Solution:

$$v\left(gal\right) = \left(0.785 \times Diameter^2 \times D \times 7.48\ gal/ft^3\right)$$

$$= 0.785 \times 70\ ft \times 70\ ft \times 30\ ft \times 7.48\ gal/ft^3$$

$$= 863{,}155\ gal$$

Note: Remember, the solution requires the result in gallons; thus, we must include 7.48 ft^3 in the operation to ensure the result in gallons.

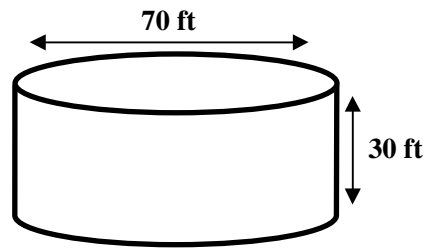

FIGURE 4.6 Circular tank. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

EXAMPLE 4.21: CYLINDRICAL TANK VOLUME

Problem:

A cylindrical tank is 12 ft in diameter and 24 ft in height. What is the approximate capacity in liters?

Note: Draw a rough diagram of the tank and label dimensions.

Solution:

$$v_{(tank)} = \frac{\pi \times d^2}{4} \times H$$

$$= \frac{\pi \times (12\ ft)^2}{4} \times 24\ ft$$

$$= 2713\ ft^3$$

Note: Remember, the problem asked for the tank capacity in liters.

Convert 2713 ft^3 to liters:

$$= 2713 \times 7.48\ gal/ft^3 \times 3.785\ L/gal$$

$$= 76{,}810\ l$$

EXAMPLE 4.22: CHANNEL VOLUME CALCULATIONS

Note: Channels are commonly used in water and wastewater treatment operations. Channels are typically rectangular or trapezoidal in shape. For rectangular channels, use:

$$v = L \times W \times D$$

Problem:

Determine the volume of wastewater (in ft^3) in the section of rectangular channel shown in Figure 4.7 when the wastewater is 5 ft deep.

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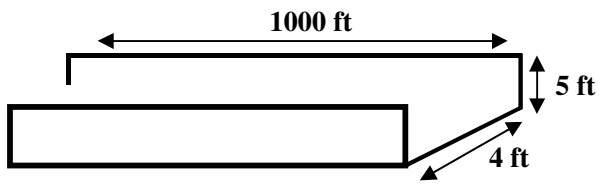

FIGURE 4.7 Open channel. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Solution:

$$v\left(ft^3\right) = L \times W \times D = 600 \text{ ft} \times 6 \text{ ft} \times 5 \text{ ft}$$

$$= 18{,}000 \text{ ft}^3$$

EXAMPLE 4.23: CHANNEL VOLUME (TRAPEZOIDAL)

$$v\left(ft^3\right) = \frac{\left(B_1 + B_2\right)}{2} D \times L$$

where

B_1 = distance across the bottom
B_2 = distance across water surface
L = channel length
D = depth of water and wastewater

Problem:

Determine the volume of wastewater (in gallons) in a section of trapezoidal channel when the wastewater depth is 5 ft.

Given:

B_1 = 4 ft across the bottom
B_2 = 10 ft across water surface
L = 1000 ft

Solution:

$$v(\text{gal}) = \frac{\left(B_1 + B_2\right)}{2} D \times L \times 7.48 \text{ gal/ft}^3$$

$$= \frac{\left(4 \text{ ft} + 10 \text{ ft}\right)}{2} 5 \text{ ft} \times 1000 \text{ ft} \times 7.48 \text{ gal/ft}^3$$

$$= 7 \times 5 \times 1000 \times 7.48$$

$$= 261{,}800 \text{ gal}$$

EXAMPLE 4.24: VOLUME OF CIRCULAR PIPELINE

$$v\left(ft^3\right) = 0785 \times \text{Diameter}^2 \times L$$

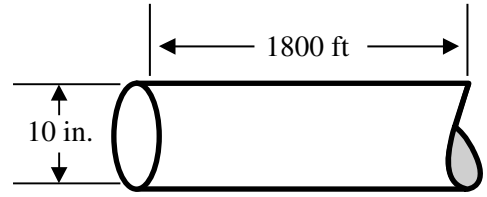

FIGURE 4.8 Circular pipe. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Problem:

What is the capacity in gallons of wastewater of a 10-in. diameter, 1800-ft section of pipeline (see Figure 4.8)?

Note: Convert 10 in. to feet (10 in./12 in./ft = .833 ft).

Solution:

$$v\ (\text{gal}) = 0785 \times \text{Diameter}^2 \times L \times 7.48 \text{ gal/ft}^3$$

$$= 0.785 \times .833 \times .833 \times 1800 \text{ ft} \times 7.48 \text{ gal/ft}^3$$

$$= 7334 \text{ gal}$$

EXAMPLE 4.25: PIPE VOLUME

Problem:

Approximately how many gallons of wastewater would 800 ft of 8-in pipe hold?

Note: Convert 8 in. to feet (8 in./12 in./ft = .67 ft).

Solution:

$$v = \frac{\pi \times \text{Diameter}^2}{4} \times L$$

$$= \frac{\pi \times 0.67^2}{4} \times 800 \text{ ft}$$

$$= 282 \text{ ft}^3$$

Convert: 282 ft^3 converted to gallons:

$$= 282 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3$$

$$= 2110 \text{ gal}$$

EXAMPLE 4.26: PIT OR TRENCH VOLUME

Note: Pits and trenches are commonly used in water and wastewater plant operations. Thus, it is important to be able to determine their volumes. The calculation used in determining pit or trench volume is similar to tank and channel

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volume calculations with one difference — the volume is often expressed as cubic yards rather than cubic feet or gallons.

In calculating cubic yards, typically two approaches are used:

1. Calculate the cubic feet volume, then convert to cubic yard volume.

$$v\left(ft^3\right) = L \times W \times D$$

$$yd^3 = \frac{ft^3}{27\ ft^3/yd}$$

2. Express all dimensions in yards so that the resulting volume calculated will be cubic yards.

$$\left(yds \times yds \times yds\right) = yd^3$$

Problem:

A trench is to be excavated 3 ft wide, 5 ft deep, and 800 ft long. What is the cubic yards volume of the trench?

Note: Remember, draw a diagram similar to the one shown in Figure 4.9.

Solution:

$$v\left(ft^3\right) = L \times W \times D$$

$$= 800\ ft \times 3\ ft \times 5\ ft$$

$$= 12{,}000\ ft^3$$

Now convert ft^3 volume to yd^3:

$$= \frac{12{,}000\ ft^3}{27\ ft^3/yd^3}$$

$$= 444\ yd^3$$

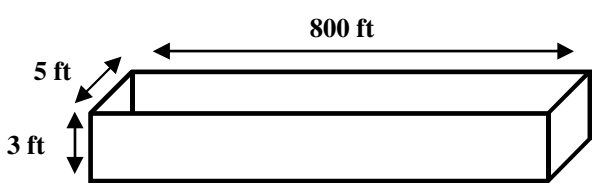

FIGURE 4.9 Trench. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Example 4.27: Trench Volume

Problem:

What is the cubic yard volume of a trench 600 ft long, 2.5 ft wide, and 4 ft deep?

Solution:

Convert dimensions in ft to yds before beginning the volume calculation:

$$L = \frac{600\ ft}{3\ ft/yd} = 200\ yd$$

$$W = \frac{2.5\ ft}{3\ ft/yd} = 0.83\ yd$$

$$D = \frac{5\ ft}{3\ ft/yd} = 1.67\ yd$$

$$v\left(yd^3\right) = L \times W \times D$$

$$= 200\ yd \times 0.83\ yd \times 1.67\ yd$$

$$= 277\ yd^3$$

Example 4.28: Pond Volumes

Ponds and/or oxidation ditches are commonly used in wastewater treatment operations. To determine the volume of a pond (or ditch) it is necessary to determine if all four sides slope or if just two sides slope. This is important because the means used to determine volume would vary depending on the number of sloping sides.

If only two of the sides slope and the ends are vertical, we calculate the volume using the equation:

$$v\left(ft^3\right) = \frac{\left(B_1 + B_2\right)}{2} D \times L$$

However, when all sides slope as shown in Figure 4.10, the equation we use must include average length and average width dimensions. The equation:

$$v\left(gal\right) = \frac{\left(B_1 + B_2\right)}{2} D \times L \times 7.48\ gal/ft^3$$

Problem:

A pond is 6 ft deep with side slopes of 2:1 (2 ft horizontal: 1 ft vertical). Using the data supplied in Figure 4.10, calculate the volume of the pond in cubic feet.

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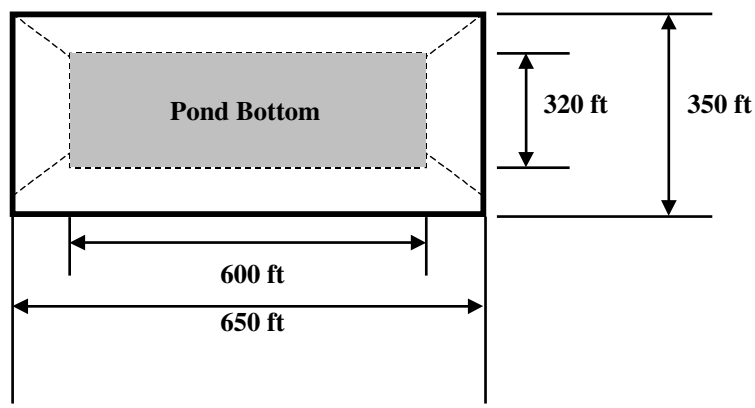

FIGURE 4.10 Pond. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

Solution:

$$v = \frac{(L_1 + L_2)}{2} \times \frac{(W_1 + W_2)}{2} \times D$$

$$= \frac{(600\text{ ft} + 650\text{ ft})}{2} \times \frac{(320\text{ ft} + 350\text{ ft})}{2} \times 6\text{ ft}$$

$$= 625\text{ ft} \times 335\text{ ft} \times 6\text{ ft}$$

$$= 1{,}256{,}250\text{ ft}^3$$

4.6 FORCE, PRESSURE, AND HEAD

Force, pressure, and head are important parameters in water and wastewater operations. Before we study calculations involving the relationship between force, pressure, and head, we must first define these terms.

1. Force — the push exerted by water on any confining surface. Force can be expressed in pounds, tons, grams, or kilograms.
2. Pressure — the force per unit area. The most common way of expressing pressure is in pounds per square inch (psi).
3. Head — the vertical distance or height of water above a reference point. Head is usually expressed in feet. In the case of water, head and pressure are related.

Figure 4.11 illustrates these terms. A cubical container measuring one foot on each side can hold one cubic foot of water. A basic fact of science states that 1 ft^3 H_2O weights 62.4 lb. The force acting on the bottom of the container would be 62.4 lb. The pressure acting on the bottom of the container would be 62.4 lb/ft^2. The area of the bottom in square inches is:

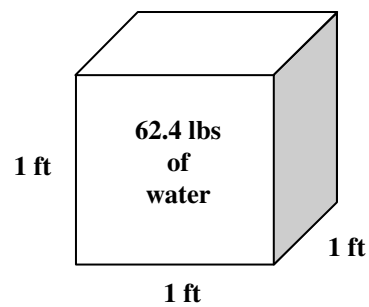

FIGURE 4.11 One cubic foot of water weighs 62.4 lbs. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

$$1\text{ ft}^2 = 12\text{ in.} \times 12\text{ in.} = 144\text{ in.}^2 \qquad (4.13)$$

Therefore the pressure in pounds per square inch (psi) is:

$$\frac{62.4\text{ lb/ft}^2}{1\text{ ft}^2} = \frac{62.4\text{ lb/ft}^2}{144\text{ in.}^2/\text{ft}^2} = 0.433\text{ psi} \qquad (4.14)$$

If we use the bottom of the container as our reference point, the head would be one foot. From this we can see that one foot of head is equal to 0.433 psi.

Note: In water and wastewater operations, 0.433 psi is an important parameter.

Figure 4.12 illustrates some other important relationships between pressure and head.

Note: Force acts in a particular direction. Water in a tank exerts force down on the bottom and out of the sides. Pressure acts in all directions. A marble at a water depth of one foot would have 0.433 psi of pressure acting inward on all sides.

Key Point: 1 ft of head = 0.433 psi.

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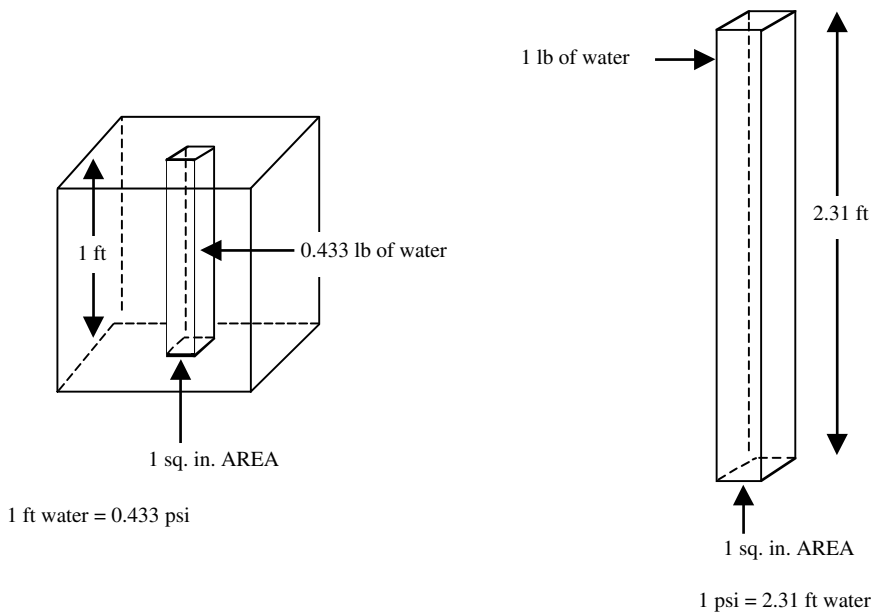

FIGURE 4.12 Shows the relationship between pressure and head. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1–3, Technomic Publ., Lancaster, PA, 1999.)

The parameter, 1 ft of head = 0.433 psi, is valuable and should be committed to memory. You should also know the relationship between pressure and feet of head — in other words, how many feet of head 1-psi represents. This is determined by dividing 1 by 0.433.

$$\text{feet of head} = \frac{1\ \text{ft}}{0.433\ \text{psi}} = 2.31\ \text{ft/psi}$$

What we are saying here is that if a pressure gauge were reading 12 psi, the height of the water necessary to represent this pressure would be 12 psi × 2.31 ft/psi = 27.7 ft.

Note: Again, the key points: 1 ft = 0.433 psi, and 1 psi = 2.31 ft

Having two conversion methods for the same thing is often confusing. Thus, memorizing one and staying with it is best. The most accurate conversion is: 1 ft = 0.433 psi — the standard conversion used throughout this handbook.

EXAMPLE 4.29

Problem:

Convert 50 psi to ft of head.

Solution:

$$\frac{50\ \text{psi}}{1} \times \frac{1\ \text{ft}}{0.433\ \text{psi}} = 115.5\ \text{ft}$$

Problem:

Convert 50 ft to psi.

Solution:

$$\frac{50\ \text{psi}}{1} \times \frac{0.433\ \text{psi}}{1\ \text{ft}} = 21.7\ \text{psi}$$

As the above examples demonstrate, when attempting to convert psi to ft, we divide by 0.433; when attempting to convert feet to psi, we multiply by 0.433. The above process can be most helpful in clearing up the confusion on whether to multiply or divide. Another way, however, may be more beneficial and easier for many operators to use. Notice that the relationship between psi and feet is almost two to one. It takes slightly more than 2 ft to make 1 psi. Therefore, when looking at a problem where the data are in pressure and the result should be in feet, the answer will be at least twice as large as the starting number. For example, if the pressure were 25 psi, we intuitively know that the head is over 50 ft. Therefore, we must divide by 0.433 to obtain the correct answer.

EXAMPLE 4.30

Problem:

Convert a pressure of 55 psi to ft of head.

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Solution:

$$\frac{55 \text{ psi}}{1} \times \frac{1 \text{ ft}}{0.433 \text{ psi}} = 127 \text{ ft}$$

EXAMPLE 4.31

Problem:

Convert 14 psi to ft of head.

Solution:

$$\frac{14 \text{ psi}}{1} \times \frac{1 \text{ ft}}{0.433 \text{ psi}} = 32.3 \text{ ft}$$

EXAMPLE 4.32

Problem:

Between the top of a reservoir and the watering point, the elevation is 115 ft. What will the static pressure be at the watering point?

Solution:

$$\frac{115 \text{ ft}}{1} \times \frac{0.433 \text{ psi}}{1 \text{ ft}} = 49.8 \text{ psi}$$

Using the preceding information, we can develop the following equations for calculating pressure and head.

$$\text{Pressure (psi)} = 0.433 \times \text{Head (ft)}$$

$$\text{Head (ft)} = 2.31 \times \text{Pressure (psi)}$$

EXAMPLE 4.33

Problem:

Find the pressure (psi) in a 12-ft deep tank at a point 15 ft below the water surface.

Solution:

$$\text{Pressure (psi)} = 0.433 \times 5 \text{ ft}$$

$$= 2.17 \text{ psi (rounded)}$$

EXAMPLE 4.34

Problem:

A pressure gauge at the bottom of a tank reads 12.2 psi. How deep is the water in the tank?

Solution:

$$\text{Head (ft)} = 2.31 \times 12.2 \text{ psi}$$

$$= 28.2 \text{ ft (rounded)}$$

EXAMPLE 4.35

Problem:

What is the pressure (static pressure) 4 mi beneath the ocean surface?

Solution:

Change mi to ft, then to psi.

$$5{,}380 \text{ ft/mi} \times 4 = 21{,}120 \text{ ft}$$

$$\frac{21{,}120 \text{ ft}}{2.31 \text{ ft/psi}} = 9{,}143 \text{ psi (rounded)}$$

EXAMPLE 4.36

Problem:

A 50-ft diameter cylindrical tank contains 2.0 MG H_2O. What is the water depth? At what pressure would a gauge at the bottom read in psi?

Step 1: Change MG to ft^3:

$$\frac{2{,}000{,}000 \text{ gal}}{7.48} = 267{,}380 \text{ ft}^3$$

Step 2: Using volume, solve for depth.

$$v = 0.785 \times \text{Diameter}^2 \times D$$

$$267{,}380 \text{ ft}^3 = 0.785 \times 150^2 \times D$$

$$D = 15.1 \text{ ft}$$

EXAMPLE 4.37

Problem:

The pressure in a pipe is 70 psi. What is the pressure in feet of water? What is the pressure in lb/ft^2?

Solution:

Step 1: Convert pressure to feet of water:

$$70 \text{ psi} \times 2.31 \text{ ft/psi} = 161.7 \text{ ft of water}$$

Step 2: Convert psi to psf:

$$70 \text{ psi} \times 144 \text{ in.}^2/\text{ft}^2 = 10{,}080 \text{ lb/ft}^2$$

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EXAMPLE 4.38

Problem:

The pressure in a pipeline is 6,476 lb/ft^2. What is the head on the pipe?

$$\text{Head on pipe} = \text{ft of pressure}$$

$$\text{Pressure} = \text{Weight} \times \text{H}$$

$$6476\ \text{lb/ft}^2 = 62.4\ \text{lb/ft}^3 \times \text{H}$$

$$\text{H} = 104\ \text{ft (rounded)}$$

4.7 FLOW

Flow is expressed in many different terms (English System of measurements). The most common flow terms are:

1. Gallons per minute (gal/min)
2. Cubic foot per second (ft^3/sec)
3. Gallons per day (gal/d)
4. Million gallons per day (MGD)

In converting flow rates, the most common flow conversions are: 1 ft^3/sec = 448 gal/min and 1 gal/min = 1440 gal/d.

To convert gal/d to MGD, divide the gal/d by 1,000,000. For instance, convert 150,000 gallons to MGD:

$$\frac{150{,}000\ \text{gal/d}}{1{,}000{,}000} = 0.150\ \text{MGD}$$

In some instances, flow is given in MGD, but needed in gal/min. To make the conversion (MGD to gal/min) requires two steps.

1. Convert the gal/d by multiplying by 1,000,000
2. Convert to gal/min by dividing by the number of minutes in a day (1440 min/d)

EXAMPLE 4.39

Problem:

Convert 0.135 MGD to gal/min

Solution:

Step 1: First, convert the flow in MGD to gal/d:

$$0.135\ \text{MGD} \times 1{,}000{,}000 = 135{,}000\ \text{gal/d}$$

Step 2: Now convert to gal/min by dividing by the number of minutes in a day (24 hrs per day X 60 min per hour) = 1440 min/day:

$$\frac{135{,}000\ \text{gal/d}}{1{,}440\ \text{min/d}} = 93.8 \text{ or } 94\ \text{gal/min}$$

In determining flow through a pipeline, channel or stream, we use the following equation:

$$Q = A \times V$$

where

Q = cubic foot per second (ft^3/sec)
A = area in square feet (ft^2)
V = velocity in feet per second (ft/sec)

EXAMPLE 4.40

Problem:

Find the flow in ft^3/sec in an 8-in. line, if the velocity is 3 ft/sec.

Solution:

Step 1: Determine the cross-sectional area of the line in square feet. Start by converting the diameter of the pipe to inches.

Step 2: The diameter is 8 in.; therefore, the radius is 4 in. 4 in. is 4/12 of a foot or 0.33 ft.

Step 3: Find the area in square feet:

$$A = \pi \times r2$$

$$A = \pi \times 0.33\ \text{ft}^2$$

$$A = \pi \times 0.109\ \text{ft}^2$$

$$A = 0.342\ \text{ft}^2$$

Step 4: Use the equation, Q = A × V:

$$Q = A \times V$$

$$Q = 3\ \text{ft/sec} \times 0.342\ \text{ft}^2$$

$$Q = 1.03\ \text{ft}^3\text{/sec}$$

EXAMPLE 4.41

Problem:

Find the flow in gal/min when the total flow for the day is 75,000 gal/d.

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Solution:

$$\frac{75{,}000\ \text{gal/d}}{1{,}440\ \text{min/d}} = 52\ \text{gal/min}$$

EXAMPLE 4.42

Problem:

Find the flow in gal/min when the flow is 0.45 ft^3/sec.

Solution:

$$\frac{0.45\ \text{ft}^3/\text{sec}}{1} \times \frac{448\ \text{gal/d}}{1\ \text{ft}^3/\text{sec}} = 202\ \text{gal/min}$$

4.7.1 FLOW CALCULATIONS

In water and wastewater treatment, one of the major concerns of the operator is not only to maintain flow, but also to measure it. Normally, flow measurements are determined by metering devices. These devices measure water flow at a particular moment (instantaneous flow) or over a specified time (total flow). Instantaneous flow can also be determined mathematically. In this section, we discuss how to mathematically determine instantaneous and average flow rates and how to make flow conversions.

4.7.1.1 Instantaneous Flow Rates

In determining instantaneous flows rates through channels, tanks and pipelines, we can use Q = A × V.

Note: It is important to remember that when using an equation such as Q = A × V the units on the left side of the equation must match those units on the right side of the equation (A and V) with respect to volume (cubic feet or gallons) and time (seconds, minutes, hours, or days).

EXAMPLE 4.43

Problem:

A 4-ft wide channel has water flowing to a depth of 2 ft. If the velocity through the channel is 2 ft/sec, what are the cubic feet per second (ft^3/sec) flow rate through the channel?

Solution:

$$\begin{aligned} Q\left(\text{ft}^3/\text{sec}\right) &= A \times V\ (\text{ft/sec}) \\ &= 4\ \text{ft} \times 2\ \text{ft} \times 2\ \text{ft/sec} \\ &= 16\ \text{ft}^3/\text{sec} \end{aligned}$$

4.7.1.1.1 Instantaneous Flow into and out of a Rectangular Tank

One of the primary flow measurements water and wastewater operators are commonly required to calculate is flow through a tank. This measurement can be determined using the Q = A × V equation. For example, if the discharge valve to a tank were closed, the water level would begin to rise. If you time how fast the water rises, this would give you an indication of the velocity of flow into the tank. This information can be plugged into Q = V × A to determine the flow rate through the tank. Let us look at an example.

EXAMPLE 4.44

Problem:

A tank is 8 ft wide and 12 ft long. With the discharge valve closed, the influent to the tank causes the water level to rise 1.5 ft in 1 min. What is the gal/min flow into the tank?

Solution:

Step 1: First, calculate the ft^3/min flow rate:

$$\begin{aligned} Q\left(\text{ft}^3/\text{min}\right) &= A \times V\ (\text{ft/min}) \\ &= \left(8\ \text{ft} \times 12\ \text{ft} \times 1.5\ \text{ft/min}\right) \\ &= 144\ \text{ft}^3/\text{min} \end{aligned}$$

Step 2: Convert ft^3/min flow rate to gal/min flow rate:

$$144\ \text{ft}^3/\text{min} \times 7.48\ \text{gal/ft}^3 = 1077\ \text{gal/min}$$

How do we compute flow rate from a tank when the influent valve is closed and the discharge pump remains on, lowering the wastewater level in the tank?

First, we time the rate of this drop in wastewater level so that the velocity of flow from the tank can be calculated. Then we use the Q = A × V equation to determine the flow rate out of the tank, as illustrated in Example 4.45.

EXAMPLE 4.45

Problem:

A tank is 9 ft wide and 11 ft long. The influent valve to the tank is closed and the water level drops 2.5 ft in 2 min. What is the gal/min flow from the tank?

Drop rate = 2.5 ft/2 min = 1.25 ft/min

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Step 1: Calculate the ft^3/min flow rate:

$$Q\left(ft^3/min\right) = A \times V\left(ft/min\right)$$
$$= 9\ ft \times 12\ ft \times 1.25\ ft/min$$
$$= 124\ ft^3/min$$

Step 2: Convert ft^3/min flow rate to gal/min flow rate:

$$124\ ft^3/min \times 7.48\ gal/ft^3 = 928\ gal/min$$

4.7.1.1.2 Flow Rate into a Cylindrical Tank

We can use the same basic method to determine the flow rate when the tank is cylindrical in shape, as shown in Example 4.46.

EXAMPLE 4.46

Problem:

The discharge valve to a 25-ft diameter cylindrical tank is closed. If the water rises at a rate of 12 inches in 4 minutes, what is the gal/min flow into the tank?

Solution:

$$\text{Rise} = 12\ in. = 1\ ft$$
$$= 1\ ft/4\ min$$
$$= 0.25\ ft/min$$

Step 1: Calculate the ft^3/min flow into the tank:

$$Q\left(ft^3/min\right) = A \times V\left(ft/min\right)$$
$$= 0.785 \times 25\ ft \times 25\ ft \times 0.25\ ft/min$$
$$= 123\ ft^3/min$$

Step 2: Then convert ft^3/min flow rate to gal/min flow rate:

$$125\ ft^3/min \times 7.48\ gal/ft^3 = 920\ gal/min$$

4.7.1.2 Flow through a Full Pipeline

Flow through pipelines is of considerable interest to water distribution operators and wastewater collection workers. The flow rate can be calculated using the $Q = A \times V$. The cross-sectional area of a round pipe is a circle, so the area, A, is represented by $0.785 \times \text{diameter}^2$.

Note: To avoid errors in terms, it is prudent to express pipe diameters as feet.

EXAMPLE 4.47

Problem:

The flow through an 8-in. diameter pipeline is moving at a velocity of 4 ft/sec. What is the ft^3/sec flow rate through the full pipeline?

Convert 8 in. to feet: 8 in./12 in. = 0.67 ft

$$Q\left(ft^3/sec\right) = A \times V\left(ft/sec\right)$$
$$= 0.785 \times 0.67\ ft \times 0.67\ ft \times 4\ ft/sec$$
$$= 1.4\ ft^3/sec$$

4.7.2 VELOCITY CALCULATIONS

To determine the velocity of flow in a channel or pipeline we use the $Q = A \times V$ equation. However, to use the equation correctly we must transpose it. We simply write into the equation the information given and then transpose for the unknown (V in this case), as illustrated in Example 4.48 for channels and 4.49 for pipelines.

EXAMPLE 4.48

Problem:

A channel has a rectangular cross section. The channel is 5 ft wide with wastewater flowing to a depth of 2 ft. If the flow rate through the channel is 8500 gal/min, what is the velocity of the wastewater in the channel (ft/sec)?

Solution

Convert gal/min to ft^3/sec:

$$\frac{8500\ gal/min}{7.48\ gal \times 60\ sec} = 18.9\ ft^3/sec$$

$$Q\left(ft^3/s\right) = A \times V\left(ft/sec\right)$$

$$18.9\ cfs = 5\ ft \times 2\ ft \times x\ ft/sec$$

$$V\ (x\ ft/sec) = \frac{18.9}{5 \times 2} = 1.89\ ft/sec$$

EXAMPLE 4.49

Problem:

A full 8-in. diameter pipe delivers 250 gal/min. What is the velocity of flow in the pipeline (ft/sec)?

Solution:

Convert: 8 in/12 in to feet = 0.67 ft

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Convert gal/min to ft³/sec flow:

$$\frac{250\ \text{gal/min}}{7.48\ \text{gal/ft}^3 \times 60\ \text{sec/min}} = 0.56\ \text{ft}^3/\text{sec}$$

$$0.56\ \text{ft}^3/\text{sec} = 0.785 \times 0.67\ \text{ft} \times 0.67\ \text{ft} \times x\ \text{ft/sec}$$

$$V = \frac{0.56\ \text{ft}^3/\text{sec}}{0.785 \times 0.67 \times 0.67} = 1.6\ \text{ft/sec}$$

4.7.3 Average Flow Rate Calculations

Flow rates in water and wastewater systems vary considerably during the course of a day, week, month, or year. Therefore, when computing flow rates for trend analysis or for other purposes, an *average flow rate* is used to determine the typical flow rate. Example 4.50 illustrates one way to calculate an average flow rate.

Example 4.50

Problem:

The following flows were recorded for the week:

Monday	8.2 MGD
Tuesday	8.0 MGD
Wednesday	7.3 MGD
Thursday	7.6 MGD
Friday	8.2 MGD
Saturday	8.9 MGD
Sunday	7.7 MGD

What was the average daily flow rate for the week?

Solution:

$$\text{Average Daily Flow} = \frac{\text{Total of All Sample Flows}}{\text{Number of Days}}$$

$$= \frac{55.9\ \text{MGD}}{7\ \text{d}}$$

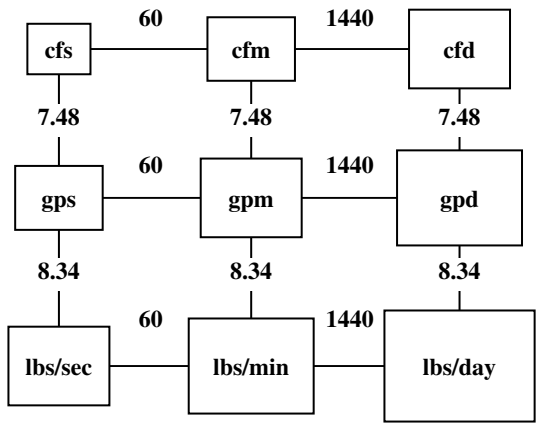
$$= 8.0\ \text{MGD}$$

4.7.4 Flow Conversion Calculations

One of the tasks involving calculations that the wastewater operator is typically called on to perform involves converting one expression of flow to another. The ability to do this is also a necessity for those preparing for licensure examinations.

Probably the easiest way in which to accomplish flow conversions is to employ the box method illustrated in Figure 4.13.

When using the box method it is important to remember that moving from a smaller box to a larger box requires multiplication by the factor indicated. Moving from a larger box to a smaller box requires division by the factor indicated.



cfs = cubic feet per second
cfm = cubic feet per minute
cfd = cubic feet per day
gps = gallons per second
gpm = gallons per minute
gpd = gallons per day

FIGURE 4.13 Flow conversions using the box method. The factors shown in the diagram have the following units associated with them: 60 sec/min, 1440 min/day, 7.48 gal./ft³, and 8.34 lbs/gal. (Adapted from Price, J.K., Applied Math for Wastewater Plant Operators, Technomic Publ., Lancaster, PA, 1991, p. 32. With permission.)

From Figure 4.13 it should be obvious that memorizing the 9 boxes and the units in each box is not that difficult. The values of 60, 1440, 7.48, and 8.34 are not that difficult to remember either — it is a matter of remembering the exact placement of the units and the values. Once this is accomplished, you have obtained a powerful tool that will enable you to make flow conversions in a relatively easy manner.

4.8 DETENTION TIME

Detention time (DT) is the length of time water is retained in a vessel or basin, or the period from the time the water enters a settling basin until it flows out the other end. To calculate the detention period of a basin, the volume of the basin must be first obtained. Using a basin 70 ft long, 25 ft wide and 12 ft deep, the volume would be:

$$v = L \times W \times D$$

$$v = 70\ \text{ft} \times 25\ \text{ft} \times 12\ \text{ft}$$

$$v = 21{,}000\ \text{ft}^3$$

$$\text{Gallons} = V \times 7.48\ \text{gal/ft}^3$$

$$\text{Gallons} = 21{,}000 \times 7.48 = 157{,}080\ \text{gal}$$

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If we assume that, the plant filters 300 gal/min, 157,080 ÷ 300 = 524 min (rounded), or roughly 9 h of detention time. Stated another way, the detention time is the length of time theoretically required for the coagulated water to flow through the basin.

If chlorine were added to the water as it entered the basin, the chlorine contact time would be 9 h. That is, to determine the contact time (CT) used to determine the effectiveness of chlorine, we must calculate detention time.

Key point: True detention time is the "T" portion of the CT value.

Note: Detention time is also important when evaluating the sedimentation and flocculation basins of a water treatment plant.

Detention time is expressed in units of time. The most common are: seconds, minutes, hours, and days.

The simplest way to calculate detention time is to divide the volume of the container by the flow rate into the container. The theoretical detention time of a container is the same as the amount of time it would take to fill the container if it were empty.

For volume, the most common units used are gallons. However, on occasion, cubic feet may also be used.

Time units will be in whatever units are used to express the flow. For example, if the flow is in gal/min, the detention time will be in days. If the detention time is in the wrong time units, simply convert to the appropriate units.

Example 4.51

Problem:

The reservoir for the community is 110,000 gal. The well will produce 60 gal/min. What is the detention time in the reservoir in hours?

Solution:

$$\text{DT} = \frac{110{,}000 \text{ gal}}{60 \text{ gal/min}} = 1834 \text{ min}$$

$$\text{or } \frac{1834 \text{ min}}{60 \text{ min/h}} = 30.6 \text{ h}$$

Example 4.52

Problem:

Find the detention time in a 55,000-gal reservoir if the flow rate is 75 gal/min.

Solution:

$$\text{DT} = \frac{55{,}000 \text{ gal}}{75 \text{ gal/min}} = 734 \text{ min}$$

$$\text{or } \frac{634 \text{ min}}{60 \text{ min/h}} = 12 \text{ h}$$

Example 4.53

Problem:

If the fuel consumption to the boiler is 30 gal/d, how many days will the 1000-gal tank last?

Solution:

$$\text{Days} = \frac{1000 \text{ gal}}{30 \text{ gal/d}} = 33.3 \text{ d}$$

4.8.1 Hydraulic Detention Time

The term detention time or hydraulic detention time (HDT) refers to the average length of time (theoretical time) a drop of water, wastewater, or suspended particles remains in a tank or channel. It is calculated by dividing the water and wastewater in the tank by the flow rate through the tank. The units of flow rate used in the calculation are dependent on whether the detention time is to be calculated in seconds, minutes, hours or days. Detention time is used in conjunction with various treatment processes, including sedimentation and coagulation-flocculation.

Generally, in practice, detention time is associated with the amount of time required for a tank to empty. The range of detention time varies with the process. For example, in a tank used for sedimentation, detention time is commonly measured in minutes.

The calculation methods used to determine detention time are illustrated in the following sections.

4.8.1.1 Detention Time in Days

The general hydraulic detention time calculation is:

$$\text{HDT} = \frac{\text{Tank Volume}}{\text{Flow Rate}} \tag{4.15}$$

This general formula is then modified based upon the information provided or available and the normal range of detention times for the unit being evaluated. Equation 4.28 shows another form of the general equation:

$$\text{HDT (d)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3}{\text{Flow (gal/d)}} \tag{4.16}$$

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Example 4.54

Problem:

An anaerobic digester has a volume of 2,200,000 gal. What is the detention time in days when the influent flow rate is 0.06 MGD?

Solution:

$$\text{DT (d)} = \frac{2{,}200{,}000 \text{ gal}}{0.06 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}$$

$$= 37 \text{ d}$$

4.8.1.2 Detention Time in Hours

$$\text{HDT (h)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3 \times 24 \text{ h/d}}{\text{Flow (gal/d)}} \quad (4.17)$$

Example 4.55

Problem:

A settling tank has a volume of 40,000 ft.^{3} What is the detention time in hours when the flow is 4.35 MGD?

Solution:

$$\text{DT (h)} = \frac{40{,}000 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 24 \text{ h/d}}{4.35 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}$$

$$= 1.7 \text{ h}$$

4.8.1.3 Detention Time in Minutes

$$\text{HDT (min)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/d}}{\text{Flow (gal/d)}} \quad (4.18)$$

Example 4.56

Problem:

A grit channel has a volume of 1240 ft.^{3} What is the detention time in minutes when the flow rate is 4.1 MGD?

Solution:

$$\text{DT (min)} = \frac{1240 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/d}}{4{,}1000{,}000 \text{ gal/d}}$$

$$= 3.26 \text{ minutes}$$

Note: The tank volume and the flow rate must be in the same dimensions before calculating the hydraulic detention time.

4.9 CHEMICAL DOSAGE CALCULATIONS

Chemicals are used extensively in water and wastewater treatment plant operations. Water and wastewater treatment plant operators add chemicals to various unit processes for slime-growth control, corrosion control, odor control, grease removal, BOD reduction, pH control, sludge-bulking control, ammonia oxidation, bacterial reduction, fluoridation, and other reasons.

In order to apply any chemical dose correctly it is important to be able to make certain dosage calculations. One of the most frequently used calculations in water and wastewater mathematics is the conversion of milligrams per liter (mg/L) concentration to pounds per day (lb/d) or pounds (lb) dosage or loading. The general types of mg/L to lb/d or lb calculations are for chemical dosage, BOD, chemical oxygen demand, or SS loading/removal, pounds of solids under aeration and WAS pumping rate. These calculations are usually made using either of the following equation 4.31 or 4.32.

$$\text{mg/L} \times \text{MGD flow} \times 8.34 \text{ lb/gal} = \text{lb/d} \quad (4.19)$$

$$\text{mg/L} \times \text{MGD volume} \times 8.34 \text{ lb/gal} = \text{lb} \quad (4.20)$$

Note: If mg/L concentration represents a concentration in a flow, then MGD flow is used as the second factor. However, if the concentration pertains to a tank or pipeline volume, then MG volume is used as the second factor.

4.9.1 Chlorine Dosage

Chlorine is a powerful oxidizer commonly used in water treatment for purification and in wastewater treatment for disinfection, odor control, bulking control, and other applications. When chlorine is added to a unit process, we want to ensure that a measured amount is added.

In describing the amount of chemical added or required two ways are used: (1) mg/L, and (2) lb/d.

In the conversion from mg/L (or ppm) concentration to lbs/day, we use equation 4.33.

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d} \quad (4.21)$$

Note: In previous years it was normal practice to use the expression parts per million (ppm) as an expression of concentration, since 1 mg/L = 1 ppm. However, current practice is to use mg/L as the preferred expression of concentration.

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Example 4.57

Problem:

Determine the chlorinator setting (lb/d) needed to treat a flow of 8 MGD with a chlorine dose of 6 mg/L.

Solution:

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d}$$

$$6\ \text{mg/L} \times 8\ \text{MGD} \times 8.34\ \text{lb/gal} = \text{lb/d}$$

$$= 400\ \text{lb/d}$$

Example 4.58

Problem:

What should the chlorinator setting be (lb/d) to treat a flow of 3 MGD if the chlorine demand is 12 mg/L and a chlorine residual of 2 mg/L is desired?

Note: The chlorine demand is the amount of chlorine used in reacting with various components of the wastewater, such as harmful organisms and other organic and inorganic substances. When the chlorine demand has been satisfied, these reactions stop.

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d}$$

Solution:

In order to find the unknown value (lb/d), we must first determine chlorine dose.

$$\text{Cl Dose}\ (\text{mg/L}) = \text{Cl Demand}\ (\text{mg/L}) + \text{Cl Residual}\ (\text{mg/L})$$

$$= 12\ \text{mg/L} + 2\ \text{mg/L}$$

$$= 14\ \text{mg/L}$$

Then we can make the mg/L to lb/d calculation:

$$12\ \text{mg/L} \times 3\ \text{MGD} \times 8.34\ \text{lb/gal} = 300\ \text{lb/d}$$

4.9.2 Hypochlorite Dosage

At many wastewater facilities sodium hypochlorite or calcium hypochlorite are used instead of chlorine. The reasons for substituting hypochlorite for chlorine vary. However, with the passage of stricter hazardous chemicals regulations under the Occupational Safety and Health Administration and the U.S. Environmental Protection Association many facilities are deciding to substitute the hazardous chemical chlorine with nonhazardous hypochlorite. Obviously, the potential liability involved with using deadly chlorine is also a factor involved in the decision to substitute it with a less toxic chemical substance.

For whatever reason the wastewater treatment plant decides to substitute chlorine for hypochlorite, there are differences between the two chemicals of which the wastewater operator needs to be aware.

Chlorine is a hazardous material. Chlorine gas is used in wastewater treatment applications at 100% available chlorine. This is an important consideration to keep in mind when making or setting chlorine feed rates. For example, if the chlorine demand and residual requires 100-lb/d chlorine, the chlorinator setting would be just that — 100-lb/24 h.

Hypochlorite is less hazardous than chlorine; it is similar to strong bleach and comes in two forms: dry HTH and liquid sodium hypochlorite. HTH contains about 65% available chlorine; sodium hypochlorite contains about 12 to 15% available chlorine (in industrial strengths).

Note: Because either type of hypochlorite is not 100% pure chlorine, more lb/day must be fed into the system to obtain the same amount of chlorine for disinfection. This is an important economic consideration for those facilities thinking about substituting hypochlorite for chlorine. Some studies indicate that such a substitution can increase operating costs, overall, by up to 3 times the cost of using chlorine.

To calculate the lb/d hypochlorite required a two-step calculation is used:

Step 1: Calculate the lb/d chlorine required using the mg/L to lb/d equation:

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d} \tag{4.22}$$

Step 2: Calculate the lb/d hypochlorite required:

$$\frac{\text{Cl}\ (\text{lb/d})}{\%\ \text{Available}} \times 100 = \text{Hypochlorite}\ (\text{lb/d}) \tag{4.23}$$

Example 4.59

Problem:

A total chlorine dosage of 10 mg/L is required to treat a particular wastewater. If the flow is 1.4 MGD and the hypochlorite has 65% available chlorine how many lb/d of hypochlorite will be required?

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Solution:

Step 1: Calculate the lb/day chlorine required using the mg/L to lb/d equation:

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d}$$

$$10\ \text{mg/L} \times 1.4\ \text{MGD} \times 8.34\ \text{lb/gal} = 117\ \text{lb/d}$$

Step 2: Calculate the lb/d hypochlorite required. Since only 65% of the hypochlorite is chlorine, more than 117 lb/d will be required:

$$\frac{117\ \text{lb/d Cl}}{65\%\ \text{Available Cl}} \times 100 = 180\ \text{lb/d hypochlorite}$$

EXAMPLE 4.60

Problem:

A wastewater flow of 840,000 gal/d requires a chlorine dose of 20 mg/L. If sodium hypochlorite (15% available chlorine) is to be used, how many lbs/day of sodium hypochlorite are required? How many gal/day of sodium hypochlorite is this?

Solution:

Step 1: Calculate the lb/day chlorine required:

$$\text{mg/L} \times \text{MGD} \times 8.34 = \text{lb/d}\ 20\ \text{mg/L} \times 0.84\ \text{MGD} \times 8.34\ \text{lb/gal} = 140\ \text{lb/d Cl}$$

Step 2: Calculate the lb/day sodium hypochlorite:

$$\frac{140\ \text{lb/d Cl}}{15\%\ \text{Available Cl}} \times 100 = 933\ \text{lb/d hypochlorite}$$

Step 3: Calculate the gal/d sodium hypochlorite:

$$\frac{933\ \text{lb/d}}{8.34\ \text{lb/gal}} = 112\ \text{gal/d sodium hypochlorite}$$

EXAMPLE 4.61

Problem:

How many pounds of chlorine gas are necessary to 5,000,000 gal of wastewater at a dosage of 2 mg/L?

Solution:

Step 1: Calculate the pounds of chlorine required:

$$\text{v}\left(10^6\ \text{gal}\right) = \text{Cl concentration}\ (\text{mg/L}) \times 8.34 = \text{lb Cl}$$

Step 2: Substitute the numbers into the equation:

$$5 \times 10^6\ \text{gal} \times 2\ \text{mg/L} \times 8.34 = 83\ \text{lb Cl}$$

4.10 PERCENT REMOVAL

Percent removal is used throughout the wastewater treatment process to express or evaluate the performance of the plant and individual treatment unit processes. The results can be used to determine if the plant is performing as expected or in troubleshooting unit operations by comparing the results with those listed in the plant's operations and maintenance manual. It can be used with either concentration or quantities (see Equations 4.24 and 4.25).

For concentrations use:

$$\%\ \text{Removal} = \frac{[\text{Influent Conc.} - \text{Eff. Conc.}] \times 100}{\text{Influent Conc.}} \quad (4.24)$$

For quantities use:

$$\%\ \text{Removal} = \frac{[\text{Influent Quantity} - \text{Eff. Quantity}] \times 100}{\text{Influent Quantity}} \quad (4.25)$$

Note: The calculation used for determining the performance (percent removal) for a digester is different from that used for performance (percent removal) for other processes such as some process residuals or biosolids treatment processes. Ensure the right formula is selected.

EXAMPLE 4.62

Problem:

The plant influent contains 259 mg/L BOD and the plant effluent contains 17 mg/L BOD. What is the percentage of BOD removal?

Solution:

$$\%\ \text{Removal} = \frac{[259\ \text{mg/L} - 17\ \text{mg/L}] \times 100}{259\ \text{mg/L}} = 93.4\%$$

4.11 POPULATION EQUIVALENT OR UNIT LOADING FACTOR

When it is impossible to conduct a wastewater characterization study and other data are unavailable, population equivalent (PE) or unit per capita loading factors are used to

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estimate the total waste loadings to be treated. If the BOD contribution of a discharger is known, the loading placed upon the wastewater treatment system in terms of equivalent number of people can be determined. The BOD contribution of a person is normally assumed to be 0.17 lb BOD/d.

$$\text{PE (people)} = \frac{\text{BOD Contribution (lb/d)}}{0.17 \text{ lb BOD/d/person}} \quad (4.26)$$

Example 4.63

Problem:

A new industry wishes to connect to the city's collection system. The industrial discharge will contain an average BOD concentration of 349 mg/L and the average daily flow will be 50,000 gal/d. What is the population equivalent of the industrial discharge?

Solution:

Step 1: Convert flow rate to MGD:

$$Flow = \frac{50{,}000 \text{ gal/d}}{1{,}000{,}000 \text{ gal/MG}} = 0.050 \text{ MGD}$$

Step 2: Calculate the population equivalent:

$$\text{PE (people)} = \frac{349 \text{ mg/L} \times 0.050 \text{ MGD} \times 8.34 \text{ lb/mg/L/MG}}{0.17 \text{ lb BOD/d/person}} = 856 \text{ people/d}$$

4.12 SPECIFIC GRAVITY

Specific gravity (sp gr) is the ratio of the density of a substance to that of a standard material under standard conditions of temperature and pressure. The standard material for gases is air, and for liquids and solids, it is water. Specific gravity can be used to calculate the weight of a gallon of liquid chemical.

$$\text{Chemical (lb/gal)} = H_2O \text{ (lb/gal)} \times \text{Chemicals sp gr} \quad (4.27)$$

Example 4.64

Problem:

The label states of the chemical states that the contents of the bottle have a specific gravity of 1.4515. What is the weight of 1 gal of solution?

Solution:

$$\text{Weight (lb/gal)} = 1.4515 \times 8.34 \text{ lb/gal} = 12.1 \text{ lb}$$

4.13 PERCENT VOLATILE MATTER REDUCTION IN SLUDGE

The calculation used to determine percent volatile matter (VM) reduction is complicated because of the changes occurring during sludge digestion.

$$\%\text{VM (reduction)} = \frac{[\%\text{VM}_{in} - \%\text{VM}_{out}] \times 100}{[\%\text{VM}_{in} - (\%\text{VM}_{in} \times \%\text{VM}_{out})]} \quad (4.28)$$

Example 4.65

Problem:

Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Data:

Raw Sludge Volatile Matter = 72%
Digested Sludge Volatile Matter = 51%

$$\%\text{VM (reduction)} = \frac{[0.72 - 0.51] \times 100}{[0.72 - (0.72 \times 0.51)]} = 59\%$$

4.14 HORSEPOWER

In water and wastewater treatment operations, horsepower (hp) is a common expression for power. One horsepower is equal to 33,000 foot pounds (ft-lb) of work/min. This value is determined, for example, for selecting a pump or combination of pumps to ensure adequate pumping capacity. Pumping capacity depends upon the flow rate desired and the feet of head against which the pump must pump (also known as effective height).

Calculations of horsepower are made in conjunction with many treatment plant operations. The basic concept from which the horsepower calculation is derived is the concept of work.

Work involves the operation of a force (lb) over a specific distance (ft). The amount of work accomplished is measured in foot-pounds:

$$\text{ft} \times \text{lb} = \text{ft-lb} \quad (4.29)$$

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The rate of doing work (power) involves a time factor. Originally, the rate of doing work or power compared the power of a horse to that of the steam engine. The rate at which a horse could work was determined to be about 550 ft-lb/sec (or expressed as 33,000 ft-lb/min). This rate has become the definition of the standard unit called horsepower (see Equation 4.44).

$$\text{Horsepower (hp)} = \frac{\text{Power (ft-lb/min)}}{33{,}000 \text{ ft-lb/min/hp}} \quad (4.30)$$

As mentioned, in water and wastewater operations, the major use of horsepower calculation is in pumping operations. When used for this purpose, the horsepower calculation can be modified as shown in Section 4.14.1.

4.14.1 Water Horsepower

The amount of power required to move a given volume of water a specified total head is known as water horsepower (Whp).

$$\text{Whp} = \frac{\text{Pump Rate (gal/min)} \times \text{Total Head (ft)} \times 8.34 \text{ lb/gal}}{33{,}000 \text{ ft-lb/min/hp}} \quad (4.31)$$

Example 4.66

Problem:

A pump must deliver 1210 gal/min to total head of 130 ft. What is the required water horsepower?

Solution:

$$\text{Whp} = \frac{1210 \text{ gal/min} \times 130 \text{ ft} \times 8.34 \text{ lb/gal}}{33{,}000 \text{ ft-lb/min/hp}}$$

$$= 40 \text{ Whp}$$

4.14.2 Brake Horsepower

Brake horsepower (Bhp) refers to the horsepower supplied to the pump from the motor. As power moves through the pump, additional horsepower is lost from slippage and friction of the shaft and other factors; thus, pump efficiencies range from about 50 to 85% and must be taken into account.

$$\text{Bhp} = \frac{\text{Whp}}{\text{Pump \% Efficiency}} \quad (4.32)$$

Example 4.67

Problem:

Under the specified conditions, the pump efficiency is 73%. If the required water horsepower is 40 hp, what is the required brake horsepower?

$$\text{Bhp} = \frac{40 \text{ Whp}}{0.73} = 55 \text{ Bhp}$$

4.14.3 Motor Horsepower

Motor horsepower (Mhp) is the horsepower the motor must generate to produce the desired brake and water horsepower.

$$\text{Mhp} = \frac{\text{Bhp}}{\text{Motor \% Efficiency}} \quad (4.33)$$

Example 4.68

Problem:

The motor is 93% efficient. What is the required motor horsepower when the required brake horsepower is 49 Bhp?

Solution:

$$\text{Mhp} = \frac{49 \text{ Bhp}}{0.93} = 53 \text{ Mhp}$$

4.15 ELECTRICAL POWER

In this age of energy conservation, water and wastewater operators (especially senior operators) are often required to make electrical power calculations, especially regarding electrical energy required/consumed during a period. To accomplish this, horsepower is converted to electrical energy (kilowatts), and then multiplied by the hours of operation to obtain kilowatt-hours (kW-h).

$$\text{kW-h} = \text{hp} \times 0.746 \text{ kW/hp} \times \text{Operating Time (h)} \quad (4.34)$$

Example 4.69

Problem:

A 60-hp motor operates at full load 12 h/d, 7 d/week. How many kilowatts of energy does it consume per day?

Solution:

$$\text{kW-h/day} = 60 \text{ hp} \times 0.746 \text{ kW/hp} \times 12 \text{ h/d}$$

$$= 537 \text{ kW-h/day}$$

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Note: Given the cost per kilowatt-hour, the operator (or anyone else) may calculate the cost of power for any given period of operation.

$$\text{Cost} = \text{Power Required/d} \times \text{kw-h/d} \times \text{d/Period} \times \text{Cost/kW-h} \tag{4.35}$$

Example 4.70

Problem:

A 60-hp motor requires 458 kW-h/d. The pump is in operation every day. The current cost of electricity is \$0.0328/kW-h. What is the yearly electrical cost for this pump?

Solution:

$$\text{Cost (\$)} = 458 \text{ kW-d} \times 365 \text{ days/year} \times \$0.0328/\text{kW-h} = \$5483.18$$

4.16 CHEMICAL COAGULATION AND SEDIMENTATION

Chemical coagulation consists of treating the water with certain chemicals to bring nonsettleable particles together into larger heavier masses of solid material (called floc) that are then relatively easy to remove.

4.16.1 Calculating Feed Rate

The following equation is used to calculate the feed rate of chemicals used in coagulation.

$$\text{Chemical Feed Rate (lb/d)} = \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34 \tag{4.36}$$

Example 4.71

Problem:

A water treatment plant operates at a rate of 5 MGD. The dosage of alum is 40 ppm (or mg/L). How many pounds of alum are used a day?

Solution:

$$\begin{aligned}\text{Chemical Feed Rate} &= \text{Dose (mg/L)} \times \text{Flow (MGD)} \times (8.34)\\ &= 40 \text{ mg/L} \times 5 \text{ MGD} \times (8.34)\\ &= 1668 \text{ lb/d of alum}\end{aligned}$$

4.16.2 Calculating Solution Strength

Use the following procedure to calculate solution strength.

Example 4.72

Problem:

Eight pounds of alum are added to 115 lb of H_2O. What is the solution strength?

Solution:

$$70\% = \frac{8}{(8+115)} \times 100 = 6.5\% \text{ Solution}$$

We use this same concept in determining other solution strengths.

Example 4.73

Problem:

Approximately 25 lb of alum are added to 90 lb of H_2O. What is the solution strength?

Solution:

$$\frac{25}{(25+30)} \times 100 = 22\% \text{ Solution}$$

In the previous examples, we added pounds of chemicals to pounds of water. Recall that 1 gal of H_2O = 8.34 lb. By multiplying the number of gallons by the 8.34 factor, we can find pounds.

Example 4.74

Problem:

Approximately 40 lb of soda ash are added to 65 gal of H_2O. What is the solution strength?

Solution:

The units must be consistent, so convert gallons of H_2O to pounds of H_2O:

$$65 \text{ gal} \times 8.34 \text{ lb/gal} = 542.7 \text{ lb } H_2O$$

$$\frac{40}{(542.7+40)} \times 100 = 6.9\% \text{ Solution}$$

4.17 FILTRATION

In waterworks operation (and to an increasing degree in wastewater treatment), the rate of flow through filters is an important operational parameter. While flow rate can

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be controlled by various means or may proceed at a variable declining rate, the important point is that with flow suspended matter continuously builds up within the filter bed, affecting the rate of filtration.

4.17.1 Calculating the Rate of Filtration

Example 4.75

Problem:

A filter box is 20 × 30 ft (also the sand area). If the influent value is shut, the water drops 3 in./min. What is the rate of filtration in MGD?

Solution:

Given:

Filter box = 20 × 30 ft
Water drops = 3 in./min

Find the volume of water passing through the filter

$$v = A \times H$$

$$A = W \times L$$

Note: The best way to perform calculations of this type is systematic, breaking down the problem into what is given and what is to be found.

Step 1: Calculate the area; convert 3 in. to feet, and divide 3 by 12 to find feet:

$$A = 20\ \text{ft} \times 30\ \text{ft} = 600\ \text{ft}^2$$

$$3.0/12 = 0.25\ \text{ft}$$

$$v = 600\ \text{ft}^2 \times 0.25\ \text{ft}$$

$$= 150\ \text{ft}^3 \text{ of } H_2O \text{ passing through the filter in 1 min}$$

Step 2: Convert ft^3 to gal:

$$150\ \text{ft}^3 \times 7.48\ \text{gal}/\text{ft}^3 = 1122\ \text{gal}/\text{min}$$

Step 3: The problem asks for the rate of filtration in MGD. To find MGD, multiply the number of gallons per minute by the number of minutes per day.

$$1122\ \text{gal}/\text{min} \times 1440\ \text{min}/\text{d} = 1.62\ \text{MGD}$$

4.17.2 Filter Backwash

In filter backwashing, one of the most important operational parameters to be determined is the amount of water in gallons required for each backwash. This amount depends on the design of the filter and the quality of the water being filtered. The actual washing typically lasts 5 to 10 min and uses amounts of 1 to 5% of the flow produced.

Example 4.76

Problem:

A filter has the following dimensions:

L = 30 ft
W = 20 ft
Depth of filter media = 24 in.

Assuming a backwash rate of 15 gal/ft²/min per minute is recommended, and 10 minutes of backwash is required, calculate the amount of water in gallons required for each backwash.

Solution:

Given:

$$L = 30\ \text{ft}$$

$$W = 20\ \text{ft}$$

$$\text{Depth of filter media} = 24\ \text{in.}$$

$$\text{Rate} = 15\ \text{gal}/\text{ft}^2/\text{min}$$

10-min backwash time

Find the amount of water in gallons required

Step 1: Calculate the area of the filter:

$$30\ \text{ft} \times 20\ \text{ft} = 600\ \text{ft}^2$$

Step 2: Calculate the gallons of H_2O used per square foot of filter:

$$15\ \text{gal}/\text{ft}^2/\text{min} \times 10\ \text{min} = 15\ \text{gal}/\text{ft}^2$$

Step 3: Calculate the gallons required:

$$150\ \text{gal}/\text{ft}^2 \times 600\ \text{ft}^2 =$$

$$90{,}000\ \text{gal required for backwash}$$

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4.18 PRACTICAL WATER DISTRIBUTION SYSTEM CALCULATIONS

After water is adequately treated, it must be conveyed or distributed to the customer for domestic, commercial, industrial, and fire-fighting applications. Water distribution systems should be capable of meeting the demands placed on them at all times and at satisfactory pressures. Waterworks operators responsible for water distribution must be able to perform basic calculations for both practical and licensure purposes; such calculations deal with water velocity, rate of water flow, water storage tanks, and water disinfection.

4.18.1 Water Flow Velocity

The velocity of a particle (any particle) is the speed at which it is moving. Velocity is expressed by indicating the length of travel and how long it takes to cover the distance. Velocity can be expressed in almost any distance and time units.

$$V = \frac{\text{Distance Traveled}}{t} \tag{4.37}$$

Note that water flow that enters the pipe (any pipe) is the same flow that exits the pipe (under steady flow conditions). Water flow is continuous. Water is incompressible; it cannot accumulate inside. The flow at any given point is the same flow at any other given point in the pipeline.

Therefore, a given flow volume may not change (it should not), but the velocity of the water may change. At any given flow, velocity is dependent upon the cross-sectional area of the pipe or conduit. Velocity (the speed at which the flow is traveling) is an important parameter.

When dealing with velocity of flow, another most basic hydraulic equation is:

$$Q = A \times V$$

where

Q = Flow

A = Area (cross-sectional area of conduit — [0.785 × Diameter^2])

V = Velocity

Example 4.77

Problem:

A flow of 2 MGD occurs in a 10-in. diameter conduit. What is the water velocity?

Solution:

Change MGD to ft^3/sec, inches to ft; solve for velocity using Equation 4.25.

$$Q = A \times V$$

$$2 \times 1.55 = 0.785 \times 0.83^2\ V$$

$$3.1 = 0.785 \times 0.69\ V$$

$$5.7 = V$$

$$V = 5.7\ \text{ft/sec}$$

Example 4.78

Problem:

A 24-in. diameter pipe carries water at a velocity of 140 ft/min. What is the flow rate in gal/min)?

Solution:

Change ft/min to ft/sec and inches to ft; solve for flow.

$$Q = A \times V$$

$$= 0.785 \times 2^2 \times 2.3$$

$$= 7.2\ \text{ft}^3/\text{sec}$$

$$= 7.2\ \text{ft}^3/\text{sec} \times 7.48\ \text{ft}^3 \times 60\ \text{min}$$

$$= 3{,}231\ \text{gal/min}$$

Example 4.79

Problem:

If water travels 700 ft in 5 minutes, what is the velocity?

Solution:

$$v = \frac{\text{Distance Traveled}}{t}$$

$$= \frac{700\ \text{ft}}{5\ \text{min}}$$

$$= 140\ \text{ft/min}$$

Example 4.80

Problem:

Flow in a 6-in. pipe is 400 gal/min. What is the average velocity?

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Solution:

Step 1: Calculate the area. Convert 6 in. to feet by dividing by 12: 6/12 = 0.5 ft

$$A = 0.785 \times \text{Diameter}^2$$
$$= 0.785 \times 0.5^2$$
$$= 0.785 \times 0.25$$
$$= 0.196 \text{ ft}^2 \text{ (rounded)}$$

Step 2: Calculate the flow:

$$Q\left(\text{ft}^3/\text{sec}\right) = \frac{Q\left(\text{gal/min}\right) \times \text{ft}^3}{7.48 \text{ gal} \times 1 \text{ min/60 sec}}$$
$$= \frac{400 \text{ gal/min} \times \text{ft}^3}{7.48 \text{ gal} \times 1 \text{ min/60 sec}}$$
$$= \frac{400 \text{ ft}^3}{448.3 \text{ sec}}$$
$$= 0.89 \text{ ft}^3/\text{sec}$$

Step 3: Calculate the velocity:

$$V\left(\text{ft/sec}\right) = \frac{Q\left(\text{ft}^3/\text{sec}\right)}{A\left(\text{ft}^2\right)}$$
$$= \frac{0.89 \text{ ft}^3/\text{sec}}{0.196 \text{ ft}^2}$$
$$= 4.5 \text{ ft/sec}$$

Example 4.81

Problem:

Flow in a 2.0-ft wide rectangular channel is 1.2 ft deep and measures 11.0 ft^3/sec. What is the average velocity?

Solution:

Given:

Q = Rate of flow = 11.0 ft^3/sec
A = Area in ft^2
2.0 ft wide
1.2 ft deep

Find the average velocity.

Step 1: Transpose Q = VA to V = Q/A

Step 2: Calculate the area:

$$A = W \times D$$
$$= 2.0 \text{ ft} \times 1.2 \text{ ft}$$
$$= 2.4 \text{ ft}^2$$

Step 3: Calculate the velocity:

$$V\left(\text{ft/sec}\right) = \frac{Q\left(\text{ft}^3/\text{sec}\right)}{A\left(\text{ft}^2\right)}$$
$$= \frac{110 \text{ ft}^3/\text{sec}}{2.4 \text{ ft}^2}$$
$$= 4.6 \text{ ft/sec (rounded)}$$

4.18.2 Storage Tank Calculations

Water is stored at a waterworks operation to provide allowance for differences in water production rates and high-lift pump discharge to the distribution system. Water within the distribution system may be stored in elevated tanks, standpipes, covered reservoirs, and/or underground basins.

The waterworks operator should be familiar with the basic storage tank calculation illustrated in the following example.

Example 4.82

Problem:

A cylindrical tank is 120 feet high and 25 feet in diameter. How many gallons of water will it contain?

Solution:

Given:

Height = 120 ft
Diameter = 25 ft

Find the total gallons of water contained in the tank.

Step 1: Find the volume in ft^3:

$$v = 0.785 \times \text{Diameter}^2 \times H$$
$$= 0.785 \times (25 \text{ ft})^2 \times 120 \text{ ft}$$
$$= 0.785 \times 625 \text{ ft}^2 \times 120 \text{ ft}$$
$$= 58.875 \text{ ft}^3$$

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Step 2: Find the number of gallons of water the cylindrical tank will contain:

$$= 58.875 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3$$

$$= 440{,}385 \text{ gal}$$

4.18.3 Distribution System Disinfection Calculations

Before being placed in service, all facilities and appurtenances associated with the treatment and distribution of water must be disinfected. This is because water may become tainted anywhere in the system; delivering a clean, pathogen-free product to the customer is what water treatment operation is all about.

In the examples that follow, we demonstrate how to perform the necessary calculations for this procedure.

Example 4.83

Problem:

A waterworks has a tank containing water that needs to be disinfected using HTH 70% available chlorine. The tank is 100 ft high and 25 ft in diameter. The dose to use is 50 ppm. How many pounds of HTH are needed?

Solution:

Given:

H = 100 ft
Diameter = 25 ft
Cl dose = 50 ppm
Available Cl = 70%

Find the pounds of HTH

Step 1: Find the volume of the tank:

$$v = 3.14 \times r^2 \times H$$

$$r = \frac{\text{Diameter}}{2} = \frac{25 \text{ ft}}{2} = 12.5 \text{ ft}$$

$$v = 3.14 \times 12.5^2 \times 100$$

$$= 3.14 \times 156.25 \times 100$$

$$= 3.14\ (15{,}625)$$

$$= 49{,}062.5 \text{ f}^3$$

Step 2: Convert cubic feet to million gallons (MG).

$$49{,}062.5 \text{ ft}^3 \times \frac{7.48 \text{ gal}}{\text{ft}^3} = \frac{\text{MG}}{1{,}000{,}000 \text{ gal}}$$

$$= 0.367 \text{ MG}$$

$$\text{Chemical Weight (lb)} =$$

$$\text{Chemical Dose (mg/L)} \times$$

$$\text{Water Volume (MG)} \times 8.34$$

Step 3: Calculate the amount of available chlorine:

$$\text{Cl} = 50 \text{ mg/L} \times 0.367 \text{ MG} \times 8.34$$

$$= 153 \text{ lb (available)}$$

Note: The fundamental concept to keep in mind when computing hypochlorite calculations is that once we determine how many pounds of chlorine will be required for disinfection, we will always need more pounds hypochlorite as compared to elemental chlorine.

Step 4: Calculate the amount of HTH required:

$$\text{Hypochlorite} = \frac{\text{Available Chlorine}}{\text{Chlorine Fraction}}$$

$$= \frac{153 \text{ lb}}{0.7}$$

$$= 218.6 \text{ lb HTH required (rounded)}$$

Example 4.84

Problem:

When treating 4000 ft of 8-in. water line by applying enough chlorine for 80-ppm dosage, how many pounds of hypochlorite of 70% available chlorine are required?

Solution:

Given:

Length = 4000 ft
Available Cl = 70%
Diameter = 8 in.
Cl dose = 80 ppm

Find the pounds of hypochlorite required.

Step 1: Find the volume of the pipe (change 8 in. to ft by dividing by 12):

$$\text{Diameter} = \frac{8 \text{ in.}}{12 \text{ in./ft}} = 0.66 \text{ ft} = 0.70 \text{ ft (rounded)}$$

$$r = \frac{\text{Diameter}}{2} = \frac{0.70 \text{ ft}}{2} = 0.35 \text{ ft}$$

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$$v = 3.14 \times r^2 \times H$$

$$= 3.14 \times 0.35^2 \times 4000 \text{ ft}$$

$$= 3.14\,(0.1225) \times 4000 \text{ ft}$$

$$= 1538.6 \text{ ft}^3$$

Step 2: Convert ft^3 to MG:

$$1538.6 \text{ ft}^3 \times \frac{7.48 \text{ gal/ft}^3}{\text{ft}^3} = \frac{\text{MG}}{1{,}000{,}000 \text{ gal}}$$

$$= 0.0115 \text{ MG}$$

Step 3: Calculate the amount of available chlorine:

$$\text{Cl} = 80 \text{ mg/L} \times 0.0115 \text{ MG} \times 8.34$$

$$= 7.67 \text{ lb (available)}$$

Step 4: Calculate the amount of hypochlorite required:

$$\frac{7.67 \text{ lb Cl}}{0.7} = 11 \text{ lb of hypochlorite (rounded)}$$

4.19 COMPLEX CONVERSIONS

Water and wastewater operators use complex conversions, for example, in converting laboratory test results to other units of measure, which can be used to adjust or control the treatment process. Conversions such as these require the use of several measurements (i.e., concentration, flow rate, tank volume, etc.) and an appropriate conversion factor. The most widely used of these conversions are discussed in the following sections.

4.19.1 Concentration to Quantity

4.19.1.1 Concentration (Milligrams per Liter) to Pounds

$$\text{lb} = \text{Concentration (mg/L)} \times \text{Tank Volume (MG)} \times 8.34 \text{ lb/MG/mg/L} \tag{4.38}$$

Example 4.85

Problem:

Given:

MLSS = 2580 mg/L
Aeration tank volume = 0.90 MG

Find the concentration in pounds.

Solution:

$$\text{lb} = 2580 \text{ mg/L} \times 0.90 \text{ MG} \times 8.34 \text{ lb/MG/mg/L}$$

$$= 19{,}366 \text{ lb}$$

4.19.1.2 Concentration (Milligrams per Liter) to Pounds/Day

$$\text{lb/d} = \text{Concentration (mg/L)} \times \text{Q (MGD)} \times 8.34 \text{ lb/MG/mg/L} \tag{4.39}$$

Example 4.86

Problem:

Given:

Effluent BOD = 23 mg/L
Effluent flow = 4.85 MGD

Find the concentration in lb/d.

Solution:

$$\text{lb/d} = 23 \text{ mg/L} \times 4.85 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L}$$

$$= 930 \text{ lb/d}$$

4.19.1.3 Concentration (Milligrams per Liter) to Kilograms per Day

$$\text{kg/d} = \text{Concentration (mg/L)} \times \text{Q (MGD)} \times 3.785 \text{ lb/MG/mg/L} \tag{4.40}$$

Example 4.87

Problem:

Given:

Effluent TSS = 29 mg/L
Effluent flow = 11.5 MGD

Find the concentration in kg/d.

Solution:

$$\text{kg/d} = 29 \text{ mg/L} \times 11.5 \text{ MGD} \times 3.785 \text{ lb/MG/mg/L}$$

$$= 1263 \text{ kg/d}$$

4.19.1.4 Concentration (milligrams/kilogram) to pounds/ton

$$\text{lb/ton} = \text{Concentration (mg/KG)} \times 0.002 \text{ lb/ton/mg/kg} \tag{4.41}$$

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Example 4.88

Problem:

Biosolids contain 0.97 mg/kg of lead. How many pounds of lead are being applied per acre if the current application rate is 5 dry tons of solids per acre?

Solution:

$$\text{lb/ac} = 0.97\ \text{mg/kg} \times 5\ \text{tons/ac} \times 0.002\ \text{lb/ton/mg/kg} = 0.0097\ \text{lb/ac}$$

4.19.2 Quantity to Concentration

4.19.2.1 Pounds to Concentration (Milligrams per Liter)

$$\text{Concentration}\ (\text{mg/L}) = \frac{\text{Quantity}\ (\text{lb})}{\text{v}\ (\text{MG}) \times 8.34\ \text{lb/mg/L/MG}} \tag{4.42}$$

Example 4.89

Problem:

The aeration tank contains 73,529 lb of solids. The volume of the tank is 3.20 MG. What is the concentration of solids in the aeration tank in mg/L?

Solution:

$$\text{Concentration}\ (\text{mg/L}) = \frac{73{,}529\ \text{lbs}}{3.20\ \text{MG} \times 8.34\ \text{lb/mg/L/MG}} = 2755.1\ (2755)\ \text{mg/L}$$

4.19.2.2 Pounds per Day to Concentration (Milligrams per Liter)

$$\text{Concentration}\ (\text{mg/L}) = \frac{\text{Quantity}\ (\text{lb})}{\text{Q}\ (\text{MG}) \times 8.34\ \text{lb/mg/L/MG}} \tag{4.43}$$

Example 4.90

Problem:

What is the chlorine dose in milligrams/liter when 490 lb/d of chlorine is added to an effluent flow of 11.0 MGD?

Solution:

$$\text{Dose}\ (\text{mg/L}) = \frac{490\ \text{lb/d}}{11.0\ \text{MG} \times 8.34\ \text{lb/mg/L/MG}} = 5.34\ \text{mg/L}$$

4.19.2.3 Kilograms per Day to Concentration (Milligrams per Liter)

$$\text{Concentration}\ (\text{mg/L}) = \frac{\text{Quantity}\ (\text{kg/d})}{\text{Q}\ (\text{MG}) \times 3.785\ \text{kg/mg/L/MG}} \tag{4.44}$$

4.19.3 Quantity to Volume or Flow Rate

4.19.3.1 Pounds to Tank Volume (Million Gallons)

$$\text{v}\ (\text{MG}) = \frac{\text{Quantity}\ (\text{lb})}{\text{Concentration}\ (\text{mg/L}) \times 8.34\ \text{lb/mg/L/MG}} \tag{4.45}$$

4.19.3.2 Pounds per Day to Flow (Million Gallons per Day)

$$\text{Q}\ (\text{MGD}) = \frac{\text{Quantity}\ (\text{lb/d})}{\text{Concentration}\ (\text{mg/L}) \times 8.34\ \text{lb/mg/L/MG}} \tag{4.46}$$

Example 4.91

Problem:

You must remove 8485 lb of solids from the activated sludge process. The waste activated sludge solids concentration is 5636 mg/L. How many MG must be removed?

Solution:

$$\text{Q}\ (\text{MGD}) = \frac{8485\ (\text{lb/d})}{5636\ \text{mg/L} \times 8.34\ \text{lb/mg/L/MG}} = 0.181\ \text{MGD}$$

4.19.3.3 Kilograms per Day to Flow (Million Gallons per Day)

$$\text{Q}\ (\text{MG}) = \frac{\text{Quantity}\ (\text{kg/d})}{\text{Concentration}\ (\text{mg/L}) \times 3.785\ \text{kg/MG/mg/L}} \tag{4.47}$$

4.20 CHAPTER REVIEW QUESTIONS AND PROBLEMS

Basic Math Questions

4.1. Fractions are used to express a portion of a _____.

4.2. In 1.2, 1.6, 1.9, 1.8, 1.0, 1.5, what is the mean?

4.3. [(25 – 4 – 6) ÷ (3 × 5)] + 4 × 3 =

4.4. 2/3 is equal to how many ninths (x/9):

4.5. 3/4 × 5/6 =

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4.6. 3/7 ÷ 2/3 =
4.7. What is the fraction equivalent of 0.625?
4.8. What is the decimal equivalent of 3/4?
4.9. Write 10,000,000 as powers of ten.
4.10. What is the area of a rectangle 9 × 30 ft?
4.11. What is the volume of a tank 25 × 60 × 8 ft deep?
4.12. A pipe has a diameter of 8 in. Water is flowing through it at 4 ft/min. How much water is passing through in 1 min? In 1 h?
4.13. Find the volume of a fuel tank 5 ft in diameter and 12 ft long.
4.14. A reservoir is 40 ft deep. What will the pressure be at the bottom of the reservoir?
4.15. The term _____ base is used to identify the bottom leg of a triangle.
4.16. The distance from the center of a circle to the edge is the _____.
4.17. The distance around a circular object is called _____ while the distance around areas other than circles is the _____.
4.18. What do the key words: of, and, per, and less than mean in solving math problems?
4.19. When no grouping is given, in what order are problems worked?

Typical Unit Process Calculations

4.20. The sludge contains 6.55% solids. If 9000 gal of sludge are removed from the primary settling tank, how many pounds of solids are removed?
4.21. The operator wishes to remove 3440 lb/d of solids from the activated sludge process. The waste activated sludge concentration is 3224 mg/L. What is the required flow rate in MGD?
4.22. The plant influent includes an industrial flow that contains 240 mg/L BOD. The industrial flow is 0.90 MGD. What is the population equivalent for the industrial contribution in people per day?
4.23. Determine the per capita characteristics of BOD and SS, if garbage grinders are installed in a community. Assume that the average per capita flow is 120 gal/d and that the typical average per capita contributions for domestic wastewater with ground kitchen wastes are BOD: 0.29 lb/capita/d; SS: is 0.22 lb/capita/d.
4.24. The label of hypochlorite solution states that the specific gravity of the solution is 1.1347. What is the weight of 1 gal of the hypochlorite solution?
4.25. The digester has a diameter of 60 ft and is 26 ft deep. If the operator pumps 5200 gallons of residuals (sludge) to the digester per day, what is the HDT in the digester in days?
4.26. If 4000 gal of solids are removed from the primary settling tank, how many pounds of solids are removed?
4.27. The plant influent contains 240 mg/L BOD, the primary effluent contains 180 mg/L BOD, and the final effluent contains 22 mg/L BOD. What is the percent removal for the primary treatment process and for the entire plant?
4.28. The plant influent includes an industrial flow that contains 335 mg/L BOD. The industrial flow is 0.68 MGD. What is the population equivalent of the industrial discharge in people?
4.29. The label on the chemical container states that the specific gravity is 1.1435. What is the weight of 1 gal of the chemical solution?
4.30. The influent flow rate is 5.0 MG, and the current return activated sludge flow rate is 2.0 MGD. If the SSV_{60} is 36%, what should be the return rate?
4.31. The operator determines that 12,000 lb of activated sludge must be removed from the process. The waste activated sludge solids concentration currently is 5500 mg/L. What is the required waste activated sludge flow rate in MGD and gal/min?
4.32. The plant effluent currently requires a chlorine dose of 7.0 mg/L to produce the required 1.1-mg/L chlorine residual in the chlorine contact tank. What is the chlorine demand in milligrams per liter?
4.33. The ferric chloride solution (stock solution) delivered to the plant contains 42.0% ferric chloride. Testing indicates that the optimum concentration for the working solution used in the treatment of the wastewater is 3.50%. How many gallons of stock ferric chloride solution must be used to prepare 6000 gal of working solution?
4.34. Sludge is added to a 560,000-gal digester at the rate of 12,500 gal/d. What is the sludge retention time?
4.35. What is the surface area of a circular tank with a 25 ft diameter?
4.36. What is the volume of a round tank 10 ft deep, with a 35-ft diameter?
4.37. If the same water is passing through a 200-gal tank, what is the detention time?
4.38. Find the volume of a chlorine cylinder 25 in. in diameter and 44 in. tall.

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4.39. The average daily winter demand of a community is 14,000 gal. If the summer demand is estimated to be 73% greater than the winter demand, what is the estimated summer demand?

Note: Demand (when related to use) is the amount of water used in a period. The term refers to the "demand" put onto the system to meet the needs of customers.

4.40. A reservoir is 50 ft deep. What will be the pressure at the bottom of the reservoir?

4.41. Find the flow in gal/min when the flow is 1.5 ft^3/sec.

4.42. Find the flow in a 5-in. pipe when the velocity is 1.3 ft/sec.

4.43. The sedimentation basin of a waterworks contains 6575 gallons. What is the detention time if the flow is 160 gal/min?

4.44. A sedimentation tank handles a flow of 7.5 MGD. The tank is $70 \times 20 \times 15$ ft and rectangular. What is the detention time?

4.45. A circular clarifier handles a flow of 0.85 MGD. The clarifier has a 20 ft radius and a depth of 12 ft. Find the detention time.

4.46. A filter box is 40×20 ft, which also includes the sand area. If the influent valve is shut, the water drops 4.0 in./min. What is the rate of filtration in MGD?

4.47. A pump must pump 1800 gal/min against a total head of 30 ft. What horsepower is required for this work?

4.48. The operator withdraws 5450 gal of solids from the digester. How many pounds of solids have been removed?

4.49. A total of 40 hp is required for a particular pumping application. If the pump efficiency is 80%, what is the brake horsepower required?

4.50. The plant effluent contains 38 mg/L solids. The effluent flow rate is 3.89 MGD. How many pounds per day of solids are discharged?

4.51. The label of hypochlorite solution states that the specific gravity of the solution is 1.1540. What is the weight of a gallon of the hypochlorite solution?

REFERENCE

1. Price, J.M, *Applied Math for Wastewater Plant Operators*, Technomic Publ., Lancaster, PA, 1991, p. vii.

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5 Water Hydraulics

Beginning students of water hydraulics and its principles often come to the subject matter with certain misgivings. For example, water/wastewater operators quickly learn on the job that their primary operational/maintenance concerns involves a daily routine of monitoring, sampling, laboratory testing, operation and process maintenance. How does water hydraulics relate to daily operations? The hydraulic functions of the treatment process have already been designed into the plant. Why learn water hydraulics at all?

Simply put, while having hydraulic control of the plant is obviously essential to the treatment process, maintaining and ensuring continued hydraulic control is also essential. No water/wastewater facility (and/or distribution collection system) can operate without proper hydraulic control. The operator must know what hydraulic control is and what it entails to know how to ensure proper hydraulic control. Moreover, in order to understand the basics of piping and pumping systems, water/wastewater maintenance operators must have a fundamental knowledge of basic water hydraulics.[1]

Note: The practice and study of water hydraulics is not new. Even in medieval times, water hydraulics was not new. "Medieval Europe had inherited a highly developed range of Roman hydraulic components."[2] The basic conveyance technology, based on low-pressure systems of pipe and channels, was already established. In studying modern water hydraulics, it is important to remember that the science of water hydraulics is the direct result of two immediate and enduring problems: "The acquisition of fresh water and access to continuous strip of land with a suitable gradient between the source and the destination."[3]

5.1 WHAT IS WATER HYDRAULICS?

The word hydraulic is derived from the Greek words hydro (meaning water) and aulis (meaning pipe). Originally, the term hydraulics referred only to the study of water at rest and in motion (flow of water in pipes or channels). Today it is taken to mean the flow of any liquid in a system.

What is a liquid? In terms of hydraulics, a liquid can be either oil or water. In fluid power systems used in modern industrial equipment, the hydraulic liquid of choice is oil. Some common examples of hydraulic fluid power systems include automobile braking and power steering systems, hydraulic elevators, and hydraulic jacks or lifts. Probably the most familiar hydraulic fluid power systems in water and wastewater operations are used on dump trucks, front-end loaders, graders, and earth-moving and excavation equipment. In this text, we are concerned with liquid water.

Many find the study of water hydraulics difficult and puzzling (especially those related questions on the licensure examinations), but we know it is not mysterious or difficult. It is the function or output of practical applications of the basic principles of water physics.

Because water and wastewater treatment is based on the principles of water hydraulics, concise, real-world training is necessary for operators who must operate the plant and for those sitting for state licensure/certification examinations.

5.2 BASIC CONCEPTS

$$\text{Air Pressure (@ Sea Level)} = 14.7 \text{ psi}$$

The relationship shown above is important because our study of hydraulics begins with air. A blanket of air, many miles thick surrounds the earth. The weight of this blanket on a given square inch of the earth's surface will vary according to the thickness of the atmospheric blanket above that point. As shown above, at sea level, the pressure exerted is 14.7 pounds per square inch (psi). On a mountaintop, air pressure decreases because the blanket is not as thick.

$$1 \text{ ft}^3 \text{ H}_2\text{O} = 62.4 \text{ lb}$$

The relationship shown above is also important: both cubic feet and pounds are used to describe a volume of water. There is a defined relationship between these two methods of measurement. The specific weight of water is defined relative to a cubic foot. One cubic foot of water weighs 62.4 lb. This relationship is true only at a temperature of 4°C and at a pressure of 1 atm (known as standard temperature and pressure (STP) — 14.7 psi at sea level containing 7.48 gal). The weight varies so little that, for practical purposes, this weight is used from a temperature

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0°C to 100°C. One cubic inch of water weighs 0.0362 lb. Water 1 ft deep will exert a pressure of 0.43 psi on the bottom area (12 in. × 0.0362 lb/in.^{3}). A column of water two feet high exerts 0.86 psi, a column 10 ft high exerts 4.3 psi, and a column 55 ft high exerts

$$55 \text{ ft} \times 0.43 \text{ psi/ft} = 23.65 \text{ psi}$$

A column of water 2.31 ft high will exert 1.0 psi. To produce a pressure of 50 psi requires a water column

$$50 \text{ psi} \times 2.31 \text{ ft/psi} = 115.5 \text{ ft}$$

The important points being made here are:

1. 1 ft^3 H_2O = 62.4 lb (see Figure 4.11)
2. A column of water 2.31 ft high will exert 1.0 psi.

Another relationship is also important:

$$1 \text{ gal } H_2O = 8.34 \text{ lb}$$

At STP, 1 ft^3 H_2O contains 7.48 gal. With these two relationships, we can determine the weight of 1 gal H_2O. This is accomplished by

$$\text{wt 1 gal } H_2O = \frac{62.4 \text{ lb}}{7.48 \text{ gal}} = 8.34 \text{ lb/gal}$$

Thus,

$$1 \text{ gal } H_2O = 8.34 \text{ lb}$$

Note: Further, this information allows cubic feet to be converted to gallons by simply multiplying the number of cubic feet by 7.48 gal/ft.^{3}

Example 5.1

Problem:

Find the number of gallons in a reservoir that has a volume of 855.5 ft.^{3}

Solution:

$$855.5 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 6399 \text{ gal (rounded)}$$

Note: As mentioned in Chapter 4, the term head is used to designate water pressure in terms of the height of a column of water in feet. For example, a 10-ft column of water exerts 4.3 psi. This can be called 4.3-psi pressure or 10 ft of head.

5.2.1 Stevin's Law

Stevin's law deals with water at rest. Specifically, the law states: "The pressure at any point in a fluid at rest depends on the distance measured vertically to the free surface and the density of the fluid." Stated as a formula, this becomes

$$p = w \times h \tag{5.1}$$

where

p = pressure in pounds per square foot (lb/ft^2)
w = density in pounds per cubic foot (lb/ft^3)
h = vertical distance in feet

Example 5.2

Problem:

What is the pressure at a point 18 ft below the surface of a reservoir?

Solution:

Note: To calculate this, we must know that the density of the water (w) is 62.4 lb/ft^3.

$$\begin{aligned} p &= w \times h \\ &= 62.4 \text{ lb/ft}^3 \times 18 \text{ ft} \\ &= 1123 \text{ lb/ft}^2 \end{aligned}$$

Water and wastewater operators generally measure pressure in pounds per square inch rather than pounds per square foot; to convert, divide by 144 in.^{2}/ft^2 (12 in. × 12 in. = 144 in.^{2}):

$$P = \frac{1123 \text{ lb/ft}^2}{144 \text{ in.}^2/\text{ft}^2} = 7.8 \text{ psi (rounded)}$$

5.3 PROPERTIES OF WATER

Table 5.1 shows the relationship between temperature, specific weight, and the density of water.

5.3.1 Density and Specific Gravity

When we say that iron is heavier than aluminum, we say that iron has greater density than aluminum. In practice, what we are really saying is that a given volume of iron is heavier than the same volume of aluminum.

Note: What is density? Density is the mass per unit volume of a substance.

Suppose you had a tub of lard and a large box of cold cereal, each having a mass of 600 g. The density of the

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TABLE 5.1
Water Properties (Temperature, Specific Weight, and Density)

Temperature (°F)	Specific Weight (lb/ft³)	Density (slugs/ft³)
32	62.4	1.94
40	62.4	1.94
50	62.4	1.94
60	62.4	1.94
70	62.3	1.94
80	62.2	1.93
90	62.1	1.93
100	62.0	1.93
110	61.9	1.92
120	61.7	1.92
130	61.5	1.91
140	61.4	1.91
150	61.2	1.90
160	61.0	1.90
170	60.8	1.89
180	60.6	1.88
190	60.4	1.88
200	60.1	1.87
210	59.8	1.86

Source: From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.

cereal would be much less than the density of the lard because the cereal occupies a much larger volume than the lard occupies.

The density of an object can be calculated by using the formula:

$$\text{Density} = \frac{\text{Mass}}{\text{v}} \tag{5.2}$$

In water and wastewater treatment, perhaps the most common measures of density are pounds per cubic foot (lb/ft³) and pounds per gallon (lb/gal).

$$1\ \text{ft}^3\ H_2O = 62.4\ \text{lb} \ \text{—}\ \text{Density} = 62.4\ \text{lb/ft}^3$$

$$1\ \text{gal}\ H_2O = 8.34\ \text{lb} \ \text{—}\ \text{Density} = 8.34\ \text{lb/gal}$$

The density of a dry material, such as cereal, lime, soda, and sand, is usually expressed in pounds per cubic foot. The density of a liquid, such as liquid alum, liquid chlorine, or water, can be expressed either as pounds per cubic foot or as pounds per gallon. The density of a gas, such as chlorine gas, methane, carbon dioxide, or air, is usually expressed in pounds per cubic foot.

As shown in Table 5.1, the density of a substance like water changes slightly as the temperature of the substance changes. This occurs because substances usually increase in volume (size — they expand) as they become warmer. Because of this expansion with warming, the same weight is spread over a larger volume, so the density is lower when a substance is warm than when it is cold.

Note: What is specific gravity? Specific gravity is the weight (or density) of a substance compared to the weight (or density) of an equal volume of water. [Note: The specific gravity of water is 1].

This relationship is easily seen when 1 ft³ H_2O, which weighs 62.4 lb as shown earlier, is compared to 1 ft³ of aluminum, which weights 178 lb. Aluminum is 2.7 times as heavy as water.

It is not that difficult to find the specific gravity (sp gr) of a piece of metal. All you have to do is to weigh the metal in air, then weigh it under water. Its loss of weight is the weight of an equal volume of water. To find the specific gravity, divide the weight of the metal by its loss of weight in water.

$$\text{sp gr} = \frac{\text{Wt of Substance}}{\text{Wt of Equal Volume of Water}} \tag{5.3}$$

EXAMPLE 5.3

Problem:

Suppose a piece of metal weighs 150 lb in air and 85 lb underwater. What is the specific gravity?

Solution:

Step 1: Calculate the loss of weight in water:

150 lb – 85 lb = 65 lb loss of weight in H_2O

Step 2: Calculate the specific gravity

$$\text{sp gr} = \frac{150}{65} = 2.3$$

Note: In a calculation of specific gravity, it is essential that the densities be expressed in the same units.

As stated earlier, the specific gravity of water is 1.00. This is the standard — the reference to which all other liquid or solid substances are compared. Specifically, any object that has a specific gravity greater than 1.0 will sink in water (rocks, steel, iron, grit, floc, sludge). Substances with a specific gravity of less than 1.0 will float (wood, scum, gasoline). Considering the total weight and volume of a ship, its specific gravity is less than one; therefore, it can float.

The most common use of specific gravity in water and wastewater treatment operations is in gallons-to-pounds conversions. In many cases, the liquids being handled have

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a specific gravity of 1.00 or very nearly 1.00 (between 0.98 and 1.02), so 1.00 may be used in the calculations without introducing significant error. However, in calculations involving a liquid with a specific gravity of less than 0.98 or greater than 1.02, the conversions from gallons to pounds must consider specific gravity. The technique is illustrated in the following example.

EXAMPLE 5.4

Problem:

There are 1455 gal of a certain liquid in a basin. If the specific gravity of the liquid is 0.94, how many pounds of liquid are in the basin?

Solution:

Normally, for a conversion from gallons to pounds, we would use the factor 8.34 lb/gal (the density of water) if the substance's specific gravity were between 0.98 and 1.02. However, in this instance the substance has a specific gravity outside this range, so the 8.34 factor must be adjusted.

Step 1: Multiply 8.34 lb/gal by the specific gravity to obtain the adjusted factor:

$$8.34 \text{ lb/gal} \times 0.94 = 7.84 \text{ lb/gal (rounded)}$$

Step 2: Convert 1455 gal to lb using the corrected factor:

$$1455 \text{ gal} \times 7.84 \text{ lb/gal} = 11{,}407 \text{ lb (rounded)}$$

5.4 FORCE AND PRESSURE

Water exerts force and pressure against the walls of its container, whether it is stored in a tank or flowing in a pipeline. There is a difference between force and pressure, though they are closely related. Force and pressure are defined below.

Force is the push or pull influence that causes motion. In the English system, force and weight are often used in the same way. The weight of 1 ft^3 H_2O is 62.4 lb. The force exerted on the bottom of a 1-ft cube is 62.4 lb (see Figure 4.11). If we stack two cubes on top of one another, the force on the bottom will be 124.8 lb.

Pressure is a force per unit of area. In equation form, this can be expressed as:

$$P = \frac{F}{A} \tag{5.4}$$

where

P = pressure
F = force
A = area over which the force is distributed

Earlier we pointed out that pounds per square inch or pounds per square foot are common expressions of pressure. The pressure on the bottom of the cube is 62.4 lb/ft^2 (see Figure 4.11). It is normal to express pressure in pounds per square inch. This is easily accomplished by determining the weight of 1 $in.^2$ of a cube 1 ft high. If we have a cube that is 12 inches on each side, the number of square inches on the bottom surface of the cube is 12 in. × 12 in. = 144 $in.^2$ Dividing the weight by the number of square inches determines the weight on each square inch.

$$\text{psi} = \frac{62.4 \text{ lb/ft}}{144 \text{ in.}^2} = 0.433 \text{ psi/ft}$$

This is the weight of a column of water one-inch square and 1 ft tall. If the column of water were 2 ft tall, the pressure would be 2 ft × 0.433 psi/ft = 0.866 psi.

Note: 1 ft H_2O = 0.433 psi

With the above information, feet of head can be converted to pounds per square inch by multiplying the feet of head times 0.433 psi/ft.

EXAMPLE 5.5

Problem:

A tank is mounted at a height of 90 ft. Find the pressure at the bottom of the tank.

Solution:

$$90 \text{ ft} \times 0.433 \text{ psi/ft} = 39 \text{ psi (rounded)}$$

Note: To convert pounds per square inch to feet, you would divide the pounds per square inch by 0.433 psi/ft.

EXAMPLE 5.6

Problem:

Find the height of water in a tank if the pressure at the bottom of the tank is 22 psi.

Solution:

$$\text{H (ft)} = \frac{22 \text{ psi}}{0.433 \text{ psi/ft}} = 51 \text{ ft (rounded)}$$

Important Point: One of the problems encountered in a hydraulic system is storing the liquid. Unlike air, which is readily compressible and is capable of being stored in large quantities in relatively small containers, a liquid such as water cannot be compressed. Therefore, it is not possible to store a large amount of water in a small

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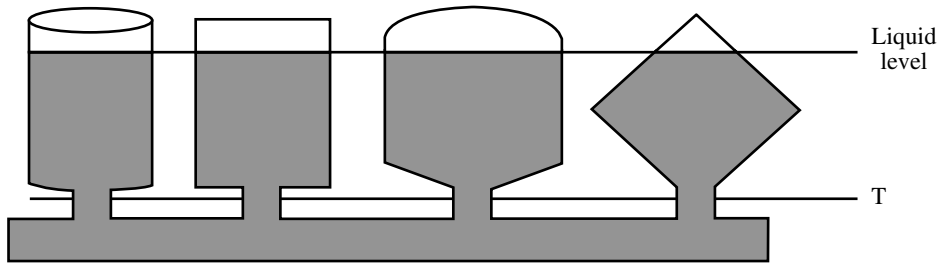

FIGURE 5.1 Hydrostatic pressure. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

tank — 62.4 lb of water occupies a volume of 1 ft^3, regardless of the pressure applied to it.

5.4.1 Hydrostatic Pressure

Figure 5.1 shows a number of differently shaped, connected, open containers of water. Note that the water level is the same in each container, regardless of the shape or size of the container. This occurs because pressure is developed, within water (or any other liquid), by the weight of the water above. If the water level in any one container were to be momentarily higher than that in any of the other containers, the higher pressure at the bottom of this container would cause some water to flow into the container having the lower liquid level. In addition, the pressure of the water at any level (such as Line T) is the same in each of the containers. Pressure increases because of the weight of the water. The further down from the surface, the more pressure is created. This illustrates that the weight, not the volume, of water contained in a vessel determines the pressure at the bottom of the vessel.

Nathanson (1997) points out some very important principles that always apply for hydrostatic pressure.

1. The pressure depends only on the depth of water above the point in question (not on the water surface area).
2. The pressure increases in direct proportion to the depth.
3. The pressure in a continuous volume of water is the same at all points that are at the same depth.
4. The pressure at any point in the water acts in all directions at the same depth.

5.4.2 Effects of Water under Pressure[5]

Water under pressure and in motion can exert tremendous forces inside a pipeline. One of these forces, called hydraulic shock or *water hammer*, is the momentary increase in pressure that occurs when there is a sudden change of direction or velocity of the water.

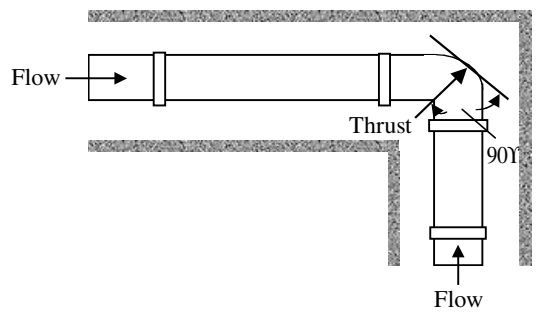

FIGURE 5.2 Shows direction of thrust in a pipe in a trench (viewed from above). (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

When a rapidly closing valve suddenly stops water flowing in a pipeline, pressure energy is transferred to the valve and pipe wall. Shockwaves are set up within the system. Waves of pressure move in a horizontal yo-yo fashion — back and forth — against any solid obstacles in the system. Neither the water nor the pipe will compress to absorb the shock, which may result in damage to pipes, valves, and shaking of loose fittings.

Another effect of water under pressure is called thrust. Thrust is the force that water exerts on a pipeline as it rounds a bend. As shown in Figure 5.2, thrust usually acts perpendicular (at 90°) to the inside surface its pushes against. As stated, it affects bends, but also reducers, dead ends, and tees. Uncontrolled, the thrust can cause movement in the fitting or pipeline, which will lead to separation of the pipe coupling away from both sections of pipeline, or at some other nearby coupling upstream or downstream of the fitting.

There are two types of devices commonly used to control thrust in larger pipelines: thrust blocks and thrust anchors. A thrust block is a mass of concrete cast in place onto the pipe and around the outside bend of the turn. An example is shown in Figure 5.3. These are used for pipes with tees or elbows that turn left or right or slant upward. The thrust is transferred to the soil through the larger bearing surface of the block.

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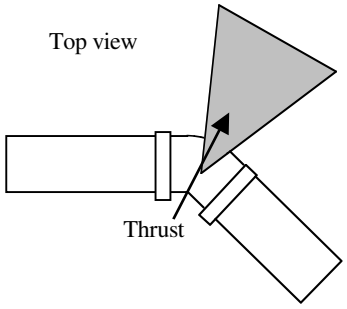

FIGURE 5.3 Thrust block. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

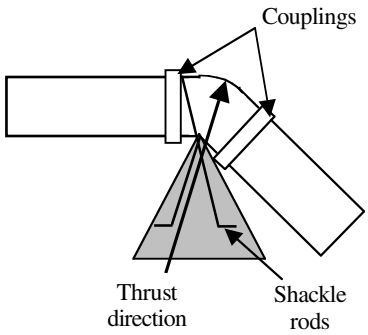

FIGURE 5.4 Thrust anchor. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

A thrust anchor is a massive block of concrete, often a cube, cast in place below the fitting to be anchored (see Figure 5.4). As shown in Figure 5.4, imbedded steel shackle rods anchor the fitting to the concrete block, effectively resisting upward thrusts.

The size and shape of a thrust control device depends on pipe size, type of fitting, water pressure, water hammer, and soil type.

5.5 HEAD

Head is defined as the vertical distance the water or wastewater must be lifted from the supply tank to the discharge, or as the height a column of water would rise due to the pressure at its base. A perfect vacuum plus atmospheric pressure of 14.7 psi would lift the water 34 ft. If the top of the sealed tube is opened to the atmosphere and the reservoir is enclosed, the pressure in the reservoir is increased; the water will rise in the tube. Because atmospheric pressure is essentially universal, we usually ignore the first 14.7-psi of actual pressure measurements, and measure only the difference between the water pressure and the atmospheric pressure; we call this *gauge pressure*. For example, water in an open reservoir is subjected to the 14.7 psi of atmospheric pressure, but subtracting this 14.7 psi leaves a gauge pressure of 0 psi. This shows that the water would rise 0 feet above the reservoir surface. If the gauge pressure in a water main were 120 psi, the water would rise in a tube connected to the main:

$$120 \text{ psi} \times 2.31 \text{ ft/psi} = 277 \text{ ft (rounded)}$$

The total head includes the vertical distance the liquid must be lifted (static head), the loss to friction (friction head), and the energy required to maintain the desired velocity (velocity head).

$$\text{Total Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \tag{5.5}$$

5.5.1 Static Head

Static head is the actual vertical distance the liquid must be lifted.

$$\text{Static Head} = \text{Discharge Elevation} \times \text{Supply Elevation} \tag{5.6}$$

Example 5.7

Problem:

The supply tank is located at elevation 118 ft. The discharge point is at elevation 215 ft. What is the static head in feet?

Solution:

$$\text{Static Head (ft)} = 215 \text{ ft} \times 118 \text{ ft} = 97 \text{ ft}$$

5.5.2 Friction Head

Friction head is the equivalent distance of the energy that must be supplied to overcome friction. Engineering references include tables showing the equivalent vertical distance for various sizes and types of pipes, fittings, and valves. The total friction head is the sum of the equivalent vertical distances for each component.

$$\text{Friction Head (ft)} = \text{Energy Losses Due to Friction} \tag{5.7}$$

5.5.3 Velocity Head

Velocity head is the equivalent distance of the energy consumed in achieving and maintaining the desired velocity in the system.

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$$\text{Velocity Head (ft)} = \text{Energy Losses to Maintain Velocity} \tag{5.8}$$

5.5.4 Total Dynamic Head (Total System Head)

$$\text{Total Dynamic Head} = \text{Static Head} + \text{Friction Head} + \text{Velocity Head} \tag{5.9}$$

5.5.5 Pressure/Head

The pressure exerted by water and wastewater is directly proportional to its depth or head in the pipe, tank, or channel. If the pressure is known, the equivalent head can be calculated.

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31 \text{ ft/psi} \tag{5.10}$$

Example 5.8

Problem:

The pressure gauge on the discharge line from the influent pump reads 72.3 psi. What is the equivalent head in feet?

Solution:

$$\text{Head (ft)} = 72.3 \text{ psi} \times 2.31 \text{ ft/psi} = 167 \text{ ft}$$

5.5.6 Head/Pressure

If the head is known, the equivalent pressure can be calculated using the following equation:

$$\text{Pressure (psi)} = \frac{\text{Head (ft)}}{2.31 \text{ ft/psi}} \tag{5.11}$$

Example 5.9

Problem:

The tank is 22 ft deep. What is the pressure in psi at the bottom of the tank when it is filled with water?

Solution:

$$\text{Pressure (psi)} = \frac{22 \text{ ft}}{2.31 \text{ ft/psi}}$$

$$= 9.52 \text{ psi (rounded)}$$

5.6 FLOW/DISCHARGE RATE: WATER IN MOTION

The study of fluid flow is much more complicated than that of fluids at rest, but it is important to have an understanding of these principles. This is because the water in a waterworks and distribution system and in a wastewater treatment plant and collection system is nearly always in motion.

Discharge (or flow) is the quantity of water passing a given point in a pipe or channel during a given period. This is stated another way for open channels: the flow rate through an open channel is directly related to the velocity of the liquid and the cross-sectional area of the liquid in the channel.

$$Q = A \times V \tag{5.12}$$

where

Q = flow (discharge in cubic feet per second [ft^3/sec])

A = cross-sectional area of the pipe or channel (ft^2)

V = water velocity in feet per second (ft/sec)

Example 5.10

Problem:

The channel is 6 ft wide and the water depth is 3 ft. The velocity in the channel is 4 ft/sec. What is the discharge or flow rate in ft^3/sec?

Solution:

$$Q\left(\text{ft}^3/\text{sec}\right) = A \times V$$

$$= 6 \text{ ft} \times 3 \text{ ft} \times 4 \text{ ft/sec} = 72 \text{ ft}^3/\text{sec}$$

Discharge or flow can be recorded as gallons per day (gal/d), gallons per minute (gal/min), or cubic feet (ft^3/sec). Flows treated by many waterworks or wastewater treatment plants are large, and often referred to in million gallons per day (MGD). The discharge or flow rate can be converted from cubic feet per second to other units such as gallons per minute or million gallons per day by using appropriate conversion factors.

Example 5.11

Problem:

A pipe 12 in. in diameter has water flowing through it at 10 ft/sec. What is the discharge in (a) ft^3/sec, (b) gal/min, and (c) MGD?

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Solution:

Before we can use the basic formula (Equation 5.13), we must determine the area of the pipe. The formula for the area of a circle is

$$A = \pi \times \frac{D^2}{4} = \pi \times r^2$$

where

D = diameter of the circle in feet
r = radius of the circle in feet
π = the constant value 3.14159 (or simply 3.14)

Therefore, the area of the pipe is:

$$A = \pi \times \frac{D^2}{4} = 3.14 \times \frac{(1\text{ ft})^2}{4} = 0.785\text{ ft}^2$$

Now we can determine the discharge in ft^3/sec (part [a]):

$$Q = A \times V = 0.785\text{ ft}^2 \times 10\text{ ft/sec} = 7.85\text{ ft}^3/\text{sec}$$

For part (b), we need to know that 1 ft^3/sec is 449 gal/min, so 7.85 ft^3/sec × 449 gal/min/ft^3/sec = 3525 gal/min (rounded).

Finally, for part (c), 1 MGD is 1.55 ft^3/sec, so:

$$\frac{7.85\text{ ft}^3/\text{sec}}{1.55\text{ ft}^3/\text{sec/MGD}} = 5.06\text{ MGD}$$

Note: Flow may be laminar (streamline — see Figure 5.5) or turbulent (see Figure 5.6). Laminar flow occurs at extremely low velocities. The water moves in straight parallel lines, called streamlines, or laminae, that slide upon each other as they travel, rather than mixing up. Normal pipe flow is turbulent flow that occurs because of friction encountered on the inside of the pipe. The outside layers of flow are thrown into the inner layers; the result is that all the layers mix and are moving in different directions and at different velocities. However, the direction of flow is forward.

Note: Flow may be steady or unsteady. For our purposes, we consider steady state flow only; most of the hydraulic calculations in this manual assume steady state flow.

5.6.1 Area/Velocity

The law of continuity states that the discharge at each point in a pipe or channel is the same as the discharge at any other point (if water does not leave or enter the pipe or channel). That means that under the assumption of steady state flow, the flow that enters the pipe or channel is the same flow that exits the pipe or channel. In equation form, this becomes

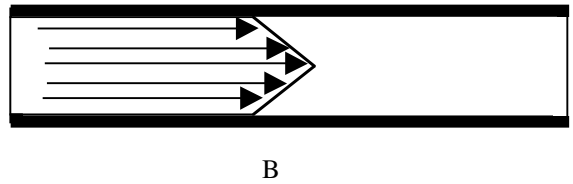

FIGURE 5.5 Laminar (streamline) flow. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

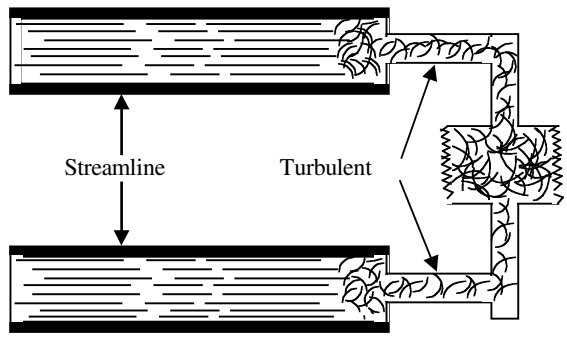

FIGURE 5.6 Turbulent flow. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

$$Q_1 = Q_2 \text{ or } A_1 \times V_1 = A_2 \times V_2 \qquad (5.13)$$

Note: In regards to the area/velocity relationship, Equation 5.13 also makes clear that for a given flow rate the velocity of the liquid varies indirectly with changes in the cross-sectional area of the channel or pipe. This principle provides the basis for many of the flow measurement devices used in open channels (weirs, flumes, and nozzles).

Example 5.12

Problem:

A pipe 12 in. in diameter is connected to a 6-in. diameter pipe. The velocity of the water in the 12-in. pipe is 3 ft/sec. What is the velocity in the 6-in. pipe?

Solution:

Using the equation $A_1 \times V_1 = A_2 \times V_2$, we need to determine the area of each pipe:

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For 12-in. pipe:

$$A = \pi \times \frac{D^2}{4}$$

$$= 3.14 \times \frac{(1\ \text{ft})^2}{4}$$

$$= 0.785\ \text{ft}^2$$

For 6-in. pipe:

$$A = 3.14 \times \frac{0.5^2}{4}$$

$$= 0.196\ \text{ft}^2$$

The continuity equation now becomes:

$$0.785\ \text{ft}^2 \times 3\text{ft/sec} = 0.196\ \text{ft}^2 \times V_2$$

Solving for V_2:

$$V_2 = \frac{0.785\ \text{ft}^2 \times 3\ \text{ft/sec}}{0.196\ \text{ft}^2} = 12\ \text{ft/sec}$$

5.6.2 Pressure/Velocity

In a closed pipe flowing full (under pressure), the pressure is indirectly related to the velocity of the liquid. This principle, when combined with the principle discussed in the previous section, forms the basis for several flow measurement devices (venturi meters and rotameters) as well as the injector used for dissolving chlorine into water, and chlorine, sulfur dioxide and/or other chemicals into wastewater.

$$\text{Velocity}_1 \times \text{Pressure}_1 = \text{Velocity}_2 \times \text{Pressure}_2 \quad (5.14)$$

or

$$V_1 \times P_1 = V_2 \times P_2$$

5.7 PIEZOMETRIC SURFACE AND BERNOULLI'S THEOREM

> They will take your hand and lead you to the pearls of the desert, those secret wells swallowed by oyster crags of wadi, underground caverns that bubble rusty salt water you would sell your own mothers to drink.[6]

To keep the systems in your plant operating properly and efficiently, you must understand the basics of hydraulics — the laws of force, motion, and others. As stated previously, most applications of hydraulics in water and wastewater treatment systems involve water in motion — in pipes under pressure or in open channels under the force of gravity. The volume of water flowing past any given point in the pipe or channel per unit time is called the flow rate or discharge, or just flow.

In regards to flow, continuity of flow and the continuity equation have been discussed (i.e., Equation 5.15). Along with the continuity of flow principle and continuity equation, the law of conservation of energy, piezometric surface, and Bernoulli's theorem (or principle) are also important to our study of water hydraulics.

5.7.1 Law of Conservation of Energy

Many of the principles of physics are important to the study of hydraulics. When applied to problems involving the flow of water, few of the principles of physical science are more important and useful to us than the law of conservation of energy. Simply, the law of conservation of energy states that energy can neither be created nor destroyed, but it can be converted from one form to another. In a given closed system, the total energy is constant.

5.7.2 Energy Head

Two types of energy, kinetic and potential, and three forms of mechanical energy exist in hydraulic systems: potential energy due to elevation, potential energy due to pressure, and kinetic energy due to velocity. Energy has the units of foot pounds (ft-lb). It is convenient to express hydraulic energy in terms of *energy head*, in feet of water. This is equivalent to foot-pounds per pound of water (ft-lb/lb H_2O = ft H_2O).

5.7.3 Piezometric Surface[7]

As mentioned earlier, we have seen that when a vertical tube, open at the top, is installed onto a vessel of water, the water will rise in the tube to the water level in the tank. The water level to which the water rises in a tube is the piezometric surface. The piezometric surface is an imaginary surface that coincides with the level of the water to which water in a system would rise in a piezometer (an instrument used to measure pressure).

The surface of water that is in contact with the atmosphere is known as free water surface. Many important hydraulic measurements are based on the difference in height between the free water surface and some point in the water system. The piezometric surface is used to locate this free water surface in a vessel, where it cannot be observed directly.

To understand how a piezometer actually measures pressure, consider the following example.

If a clear, see-through pipe is connected to the side of a clear glass or plastic vessel, the water will rise in the

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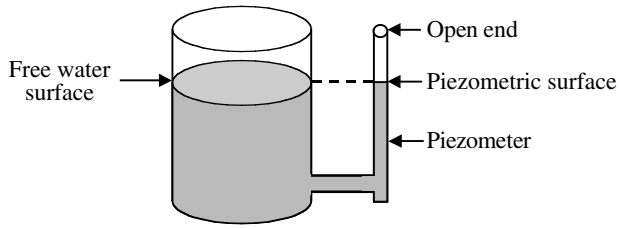

FIGURE 5.7 A container not under pressure where the piezometric surface is the same as the free water surface in the vessel. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

pipe to indicate the level of the water in the vessel. Such a see-through pipe, the piezometer, allows you to see the level of the top of the water in the pipe; this is the piezometric surface.

In practice, a piezometer is connected to the side of a tank or pipeline. If the water-containing vessel is not under pressure (as is the case in Figure 5.7), the piezometric surface will be the same as the free water surface in the vessel, just as it would if a drinking straw (the piezometer) were left standing a glass of water.

When pressurized in a tank and pipeline system, as they often are, the pressure will cause the piezometric surface to rise above the level of the water in the tank. The greater the pressure, the higher the piezometric surface (see Figure 5.8). An increased pressure in a water pipeline system is usually obtained by elevating the water tank.

Note: In practice, piezometers are not installed on water towers, because water towers are hundreds of feet high, or on pipelines. Instead, pressure gauges are used that record pressure in feet of water or in pounds per square inch.

Water only rises to the water level of the main body of water when it is at rest (static or standing water). The

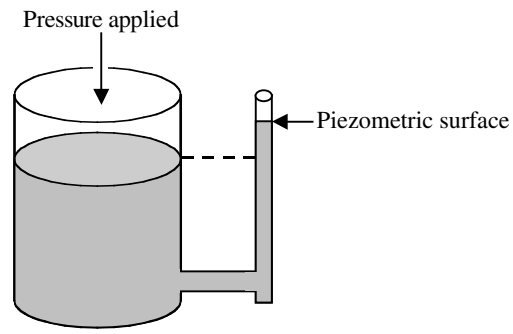

FIGURE 5.8 A container under pressure where the piezometric surface is above the level of the water in the tank. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

situation is quite different when water is flowing. Consider, for example, an elevated storage tank feeding a distribution system pipeline. When the system is at rest, all valves closed, all the piezometric surfaces are the same height as the free water surface in storage. On the other hand, when the valves are opened and the water begins to flow, the piezometric surface changes. This is an important point because as water continues to flow down a pipeline, less pressure is exerted. This happens because some pressure is lost (used up) keeping the water moving over the interior surface of the pipe (friction). The pressure that is lost is called *head loss*.

5.7.3.1 Head Loss

Head loss is best explained by example. Figure 5.9 shows an elevated storage tank feeding a distribution system pipeline. When the valve is closed (Figure 5.9A), all the piezometric surfaces are the same height as the free water surface in storage. When the valve opens and water begins to flow (Figure 5.9B), the piezometric surfaces drop. The

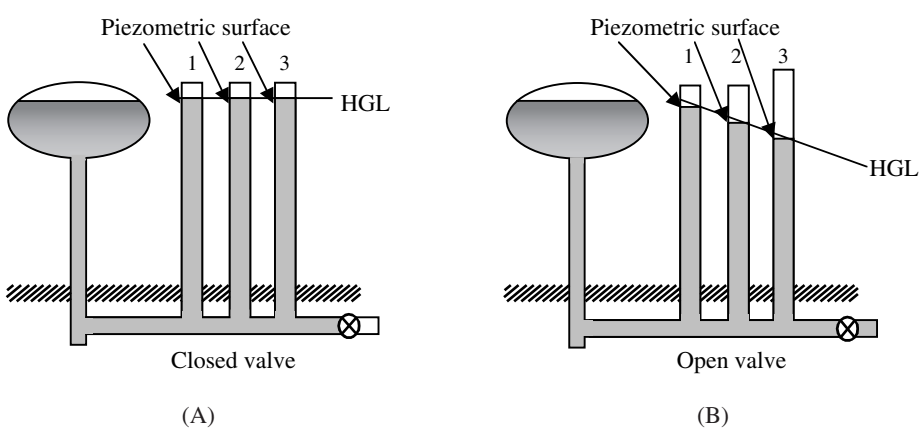

FIGURE 5.9 Shows head loss and piezometric surface changes when water is flowing. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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further along the pipeline, the lower the piezometric surface, because some of the pressure is used up keeping the water moving over the rough interior surface of the pipe. Thus, pressure is lost and is no longer available to push water up in a piezometer; this is the head loss.

5.7.3.2 Hydraulic Grade Line

When the valve is opened as in Figure 5.9, flow begins with a corresponding energy loss due to friction. The pressures along the pipeline can measure this loss. In Figure 5.9B, the difference in pressure heads between sections 1, 2, and 3 can be seen in the piezometer tubes attached to the pipe. A line connecting the water surface in the tank with the water levels at sections 1, 2, and 3 shows the pattern of continuous pressure loss along the pipeline. This is called the hydraulic grade line (HGL) or hydraulic gradient of the system. (It is important to point out that in a static water system, the HGL is always horizontal. The HGL is a very useful graphical aid when analyzing pipe flow problems.)

Note: During the early design phase of a treatment plant, it is important to establish the hydraulic grade line across the plant because both the proper selection of the plant site elevation and the suitability of the site depend on this consideration. Typically, most conventional water treatment plants required 16 to 17 ft of head loss across the plant.

Key Point: Changes in the piezometric surface occur when water is flowing.

5.7.4 Bernoulli's Theorem[8]

Swiss physicist and mathematician Samuel Bernoulli developed the calculation for the total energy relationship from point to point in a steady state fluid system in the 1700s. Before discussing Bernoulli's energy equation, it is important to understand the basic principle behind Bernoulli's equation.

Water (and any other hydraulic fluid) in a hydraulic system possesses two types of energy — kinetic and potential. Kinetic energy is present when the water is in motion. The faster the water moves, the more kinetic energy is used. Potential energy is a result of the water pressure. The total energy of the water is the sum of the kinetic and potential energy. Bernoulli's principle states that the total energy of the water (fluid) always remains constant. Therefore, when the water flow in a system increases, the pressure must decrease. When water starts to flow in a hydraulic system, the pressure drops. When the flow stops, the pressure rises again. The pressure gauges shown in Figure 5.10 indicate this balance more clearly.

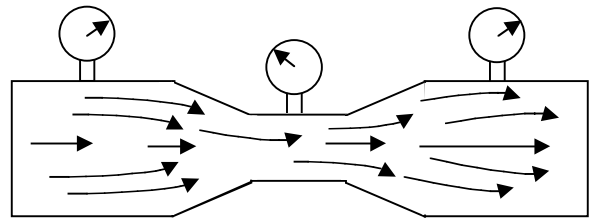

FIGURE 5.10 Demonstrates Bernoulli's principle. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

Note: The basic principle explained above ignores friction losses from point to point in a fluid system employing steady state flow.

5.7.4.1 Bernoulli's Equation

In a hydraulic system, total energy head is equal to the sum of three individual energy heads. This can be expressed as

Total Head = Elevation Head + Pressure Head + Velocity Head

where

Elevation head = pressure due to the elevation of the water
Pressure head = the height of a column of water that a given hydrostatic pressure in a system could support
Velocity head = energy present due to the velocity of the water

This can be expressed mathematically as

$$E = z + \frac{P}{w} + \frac{V^2}{2g} \tag{5.15}$$

where

E = total energy head
z = height of the water above a reference plane (ft)
P = pressure (psi)
w = unit weight of water (62.4 lb/ft^3)
V = flow velocity (ft/sec)
g = acceleration due to gravity (32.2 ft/sec^2)

Consider the constriction in section of pipe shown in Figure 5.11. We know, based on the law of energy conservation, that the total energy head at section A, E_1, must equal the total energy head at section B, E_2, and using Equation 5.16, we get Bernoulli's equation.

$$z_A = \frac{P_A}{w} + \frac{V_A^2}{2g} = z_B + \frac{P_B}{w} + \frac{V_B^2}{2g} \tag{5.16}$$

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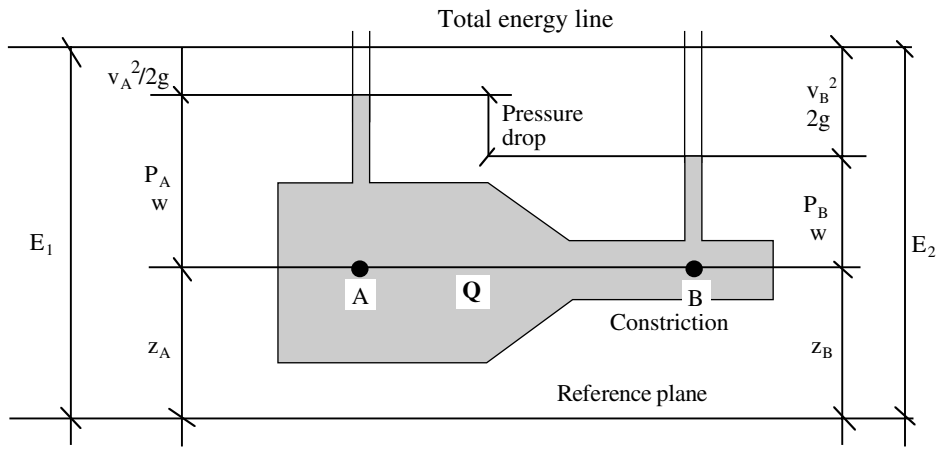

FIGURE 5.11 Shows the result of the law of conservation. Since the velocity and kinetic energy of the water flowing in the constricted section must increase, the potential energy may decrease. This is observed as a pressure drop in the constriction. (Adapted from Nathanson, J.A., Basic Environmental Technology: Water Supply, Waste Management, and Pollution Control, 2nd ed. Prentice Hall, Upper Saddle River, NJ: 1997. p. 29.)

The pipeline system shown in Figure 5.11 is horizontal. Therefore, we can simplify Bernoulli's equation because $z_A = z_B$.

Because they are equal, the elevation heads cancel out from both sides, leaving:

$$\frac{P_A}{w} + \frac{V_A^{\,2}}{2g} = \frac{P_B}{w} + \frac{V_B^{\,2}}{2g} \tag{5.17}$$

As water passes through the constricted section of the pipe (section B), we know from continuity of flow that the velocity at section B must be greater than the velocity at section A, because of the smaller flow area at section B. This means that the velocity head in the system increases as the water flows into the constricted section. However, the total energy must remain constant. For this to occur, the pressure head, and therefore the pressure, must drop. In effect, pressure energy is converted into kinetic energy in the constriction.

The fact that the pressure in the narrower pipe section (constriction) is less than the pressure in the bigger section seems to defy common sense. However, it does follow logically from continuity of flow and conservation of energy. The fact that there is a pressure difference allows measurement of flow rate in the closed pipe.

Example 5.13

Problem:

In Figure 5.11, the diameter at Section A is 8 in. and at section B, it is 4 in. The flow rate through the pipe is 3.0 ft^3/sec and the pressure at Section A is 100 psi. What is the pressure in the constriction at Section B?

Solution:

Step 1: Compute the flow area at each section, as follows:

$$A_A = \frac{\pi \times (0.666\ \text{ft})^2}{4} = 0.349\ \text{ft}^2\ (\text{rounded})$$

$$A_B = \frac{\pi \times (0.333\ \text{ft})^2}{4} = 0.087\ \text{ft}^2$$

Step 2: From Q = A × V or V = Q/A, we get:

$$V_A = \frac{3.0\ \text{ft}^3/\text{sec}}{0.349\ \text{ft}^2} = 8.6\ \text{ft/sec}\ (\text{rounded})$$

$$V_B = \frac{3.0\ \text{ft}^3/\text{sec}}{0.087\ \text{ft}^2} = 34.5\ \text{ft/sec}\ (\text{rounded})$$

Step 3: Applying Equation 5.18, we get:

$$\frac{100 \times 144}{62.4} + \frac{8.6^2}{2 \times 32.2} = \frac{P_B \times 144}{62.4} + \frac{34.5^2}{2 \times 32.2}$$

Note: The pressures are multiplied by 144 in^2/ft^2 to convert from psi to lb/ft^2 to be consistent with the units for w; the energy head terms are in feet of head.

Continuing, we get

$$231 + 1.15 = 2.3P_B + 18.5$$

and

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TABLE 5.2
Pump Applications in Water and Wastewater Systems[11]

Application	Function	Pump Type
Low service	To lift water from the source to treatment processes, or from storage to filter-backwashing system	Centrifugal
High service	To discharge water under pressure to distribution system; to pump collected or intercepted water/wastewater and pump to treatment facility	Centrifugal
Booster	To increase pressure in the distribution/collection system or to supply elevated storage tanks	Centrifugal
Well	To lift water from shallow or deep wells and discharge it to the treatment plant, storage facility, or distribution system	Centrifugal or jet
Chemical feed	To add chemical solutions at desired dosages for treatment processes	Positive displacement
Sampling	To pump water/wastewater from sampling points to the laboratory or automatic analyzers	Positive displacement or centrifugal
Sludge/biosolids	To pump sludge or biosolids from sedimentation facilities to further treatment or disposal	Positive displacement or centrifugal

Source: From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.

$$P_B = \frac{232.2 - 18.5}{2.3} = \frac{213.7}{2.3} = 93 \text{ psi (rounded)}$$

5.8 HYDRAULIC MACHINES (PUMPS)

> Only the sail can contend with the pump for the title of the earliest invention for the conversion of natural energy to useful work, and it is doubtful that the sail takes precedence. Since the sail cannot, in any event, be classified as a machine, the pump stands essentially unchallenged as the earliest form of machine that substituted natural energy for muscular effort in the fulfillment of man's needs.[9]

Conveying water and wastewater to and from process equipment is an integral part of the water and wastewater industry that requires energy consumption. The amount of energy required depends on the height to which the water or wastewater is raised, the length and diameter of the conveying conduits, the rate of flow, and the water or wastewater's physical properties (in particular, viscosity and density). In some applications, external energy for transferring water or wastewater is not required. For example, when water or wastewater flows to a lower elevation under the influence of gravity, a partial transformation of the water or wastewater's potential energy into kinetic energy occurs. However, when conveying water or wastewater through horizontal conduits, especially to higher elevations within a system, mechanical devices such as pumps are employed. Requirements vary from small units used to pump only a few gallons per minute to large units capable of handling several hundred cubic feet per second.[10] Table 5.2 lists pump applications in water and wastewater treatment operations.

Note: In determining the amount of pressure or force a pump must provide to move the water or wastewater, the term pump head was established.

Several methods are available for transporting water, wastewater, and chemicals for treatment between process equipment:

1. Centrifugal force inducing fluid motion
2. Volumetric displacement of fluids, either mechanically, or with other fluids
3. Transfer of momentum from another fluid
4. Mechanical impulse
5. Gravity induction

Depending on the facility and unit processes contained within, all of the methods above may be important to the maintenance operator.

5.8.1 Pumping Hydraulics[12]

During operation, water enters a pump on the suction side, where the pressure is lower. Since the function of the pump is to add pressure to the system, discharge pressure will always be higher. In pump systems, an important concept to keep in mind is measurements are taken from the point of reference to the centerline of the pump (horizontal line drawn through center of pump).

In order to understand pump operation, or pumping hydraulics, we need to be familiar with certain basic terms and then relate these terms pictorially (as we do in Figure 5.12) to illustrate how water is pumped from one point to another.

1. Static head — The distance between the suction and discharge water levels when the pump is shut off. We indicate static head conditions with the letter Z (see Figure 5.12).
2. Suction lift — The distance between the suction water level and the center of the pump impeller. This term is only used when the pump is in a suction lift condition; the pump must have the energy to provide this lift. A pump is said to be

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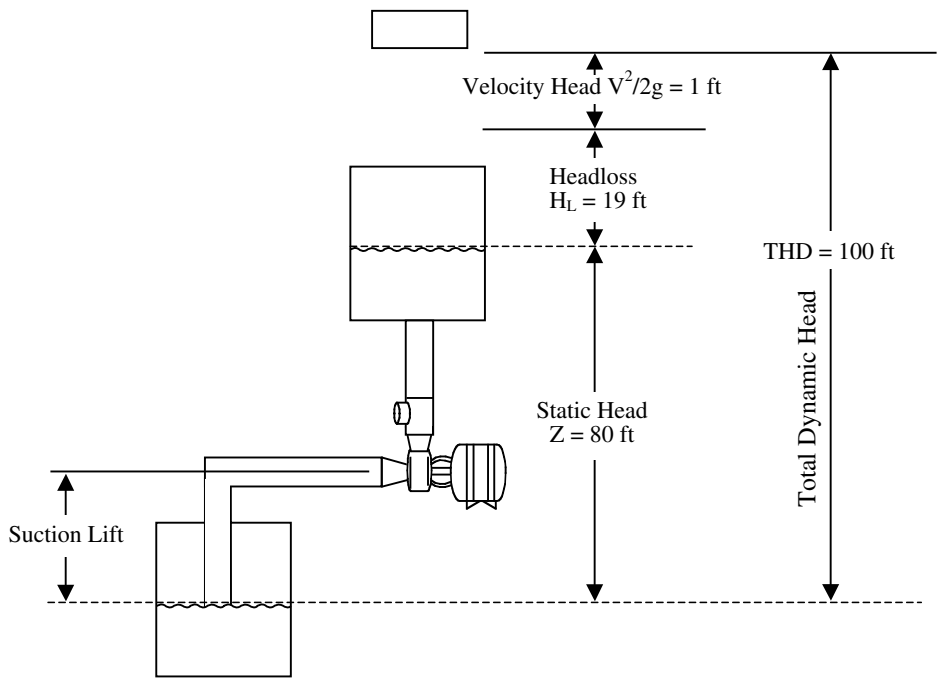

FIGURE 5.12 Components of total dynamic head. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

in a suction lift condition any time the center (eye) of the impeller is above the water being pumped (see Figure 5.12).

3. Suction head — A pump is said to be in a suction head condition any time the center (eye) of the impeller is below the water level being pumped. Specifically, suction head is the distance between the suction water level and the center of the pump impeller when the pump is in a suction head condition (see Figure 5.12).
4. Velocity head — The amount of energy required to bring water or wastewater from standstill to its velocity. For a given quantity of flow, the velocity head will vary indirectly with the pipe diameter. Velocity head is often shown mathematically as $V^2/2g$ (see Figure 5.12).
5. Total dynamic head — The total energy needed to move water from the centerline of a pump (eye of the first impeller of a lineshaft turbine) to some given elevation or to develop some given pressure. This includes the static head, velocity head and the head loss due to friction (see Figure 5.12).

5.9 WELL AND WET WELL HYDRAULICS

When the source of water for a water distribution system is from a groundwater supply, knowledge of well hydraulics is important to the operator. Basic well hydraulics terms are presented and defined, and they are related pictorially in Figure 5.13. Also discussed are wet wells, which are important, both in water and wastewater operations.

5.9.1 WELL HYDRAULICS

1. Static water level — The water level in a well when no water is being taken from the groundwater source (i.e., the water level when the pump is off; see Figure 5.13). Static water level is normally measured as the distance from the ground surface to the water surface. This is an important parameter because it is used to measure changes in the water table.
2. Pumping water level — The water level when the pump is off. When water is pumped out of a well, the water level usually drops below the level in the surrounding aquifer and eventually stabilizes at a lower level; this is the pumping level (see Figure 5.13).
3. Drawdown — the difference, or the drop, between the static water level and the pumping water level, measured in feet. Simply, it is the distance the water level drops once pumping begins (see Figure 5.13).
4. Cone of depression — In unconfined aquifers, there is a flow of water in the aquifer from all directions toward the well during pumping. The free water surface in the aquifer then takes the shape of an inverted cone or curved funnel line.

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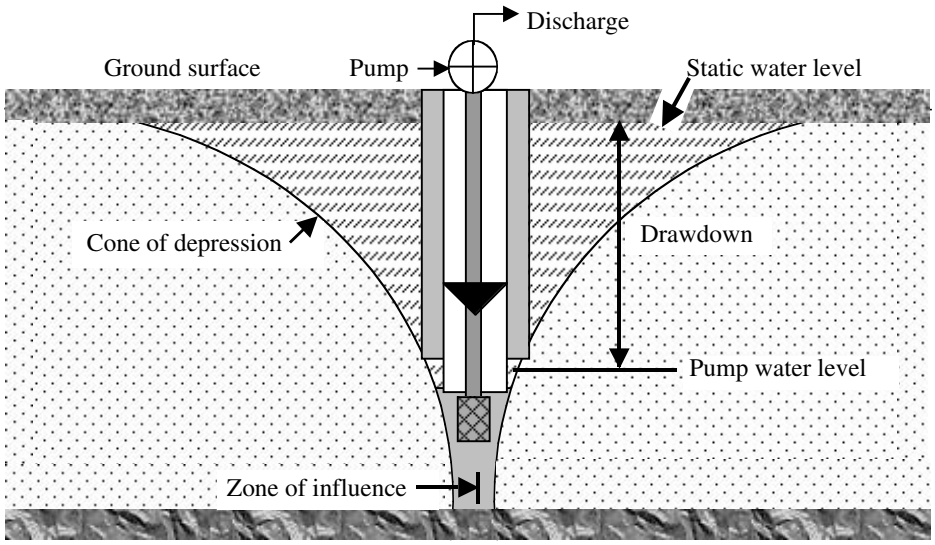

FIGURE 5.13 Hydraulic characteristics of a well. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

The curve of the line extends from the pumping water level to the static water level at the outside edge of the zone (or radius) of influence (see Figure 5.13).

Note: The shape and size of the cone of depression is dependent on the relationship between the pumping rate and the rate at which water can move toward the well. If the rate is high, the cone will be shallow and its growth will stabilize. If the rate is low, the cone will be sharp and continue to grow in size.

5. Zone (or radius) of influence — The distance between the pump shaft and the outermost area affected by drawdown (see Figure 5.13). The distance depends on the porosity of the soil and other factors. This parameter becomes important in well fields with many pumps. If wells are set too close together, the zones of influence will overlap, increasing the drawdown in all wells. Obviously, pumps should be spaced apart to prevent this from happening.

Note: Two important parameters not shown in Figure 5.13 are well yield and specific capacity.

1. Well yield is the rate of water withdrawal that a well can supply over a long period. Alternatively, this is simply the maximum pumping rate that can be achieved without increasing the drawdown. The yield of small wells is usually measured in gallons per minute (liters per minute) or gallons per hour (liters per hour). For large wells, it may be measured in cubic feet per second (cubic meters per second).
2. Specific capacity is the pumping rate per foot of drawdown (gallon per minute per foot), or

$$\text{Specific Capacity} = \frac{\text{Well Yield}}{\text{Drawdown}} \tag{5.18}$$

EXAMPLE 5.14

Problem:

If the well yield is 300 gal/min and the drawdown is measured to be 20 ft, what is the specific capacity?

Solution:

$$\text{Specific Capacity} = \frac{300}{20}$$

$$= 15 \text{ gal/min/ft of drawdown}$$

Specific capacity is one of the most important concepts in well operation and testing. The calculation should be made frequently in the monitoring of well operation. A sudden drop in specific capacity indicates problems such as pump malfunction, screen plugging, or other problems that can be serious. Such problems should be identified and corrected as soon as possible.

5.9.2 WET WELL HYDRAULICS

Water pumped from a wet well by a pump set above the water surface exhibits the same phenomena as the groundwater well. In operation, a slight depression of the water surface forms right at the intake line (drawdown), but in

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this case it is minimal because there is free water at the pump entrance at all times (at least there should be). The most important consideration in wet well operations is to ensure that the suction line is submerged far enough below the surface, so that air entrained by the active movement of the water at this section is not able to enter the pump.

Because water or wastewater flow is not always constant or at the same level, variable speed pumps are commonly used in wet well operations, or several pumps are installed for single or combined operation. In many cases, pumping is accomplished in an on/off mode. Control of pump operation is in response to water level in the well. Level control devices, such as mercury switches, are used to sense a high and low level in the well and transmit the signal to pumps for action.

5.10 FRICTION HEAD LOSS

Materials or substances capable of flowing cannot flow freely. Nothing flows without encountering some type of resistance. Consider electricity, the flow of free electrons in a conductor. Whatever type of conductor used (i.e., copper, aluminum, silver, etc.) offers some resistance. In hydraulics, the flow of water or wastewater is analogous to the flow of electricity. Within a pipe or open channel, for instance, flowing water, like electron flow in a conductor, encounters resistance. However, resistance to the flow of water is generally termed friction loss (or more appropriately, head loss).

5.10.1 Flow in Pipelines

The problem of waste and wastewater flow in pipelines — the prediction of flow rate through pipes of given characteristics, the calculation of energy conversions therein, and so forth — is encountered in many applications of water and wastewater operations and practice. Although the subject of pipe flow embraces only those problems in which pipes flow completely full (as in water lines), we also address pipes that flow partially full (wastewater lines, normally treated as open channels) in this section.

The solution of practical pipe flow problems resulting from application of the energy principle, the equation of continuity, and the principle and equation of water resistance are also discussed. Resistance to flow in pipes is not only the result of long reaches of pipe but is also offered by pipe fittings, such as bends and valves, that dissipate energy by producing relatively large-scale turbulence.

5.10.2 Pipe and Open Flow Basics

In order to gain understanding of what friction head loss is all about, it is necessary to review a few terms presented earlier in the text and to introduce some new terms pertinent to the subject.[13]

1. Laminar flow — Laminar flow is ideal flow; that is, water particles moving along straight, parallel paths, in layers or streamlines. Moreover, in laminar flow there is no turbulence in the water and no friction loss. This is not typical of normal pipe flow because the water velocity is too great, but is typical of groundwater flow.
2. Turbulent flow — Characterized as normal for a typical water system, turbulent flow occurs when water particles move in a haphazard fashion and continually cross each other in all directions resulting in pressure losses along a length of pipe.
3. Hydraulic grade line (HGL) — Recall that the hydraulic grade line (HGL) (shown in Figure 5.14) is a line connecting two points to which the liquid would rise at various places along any pipe or open channel if piezometers were inserted in the liquid. It is a measure of the pressure head available at these various points.

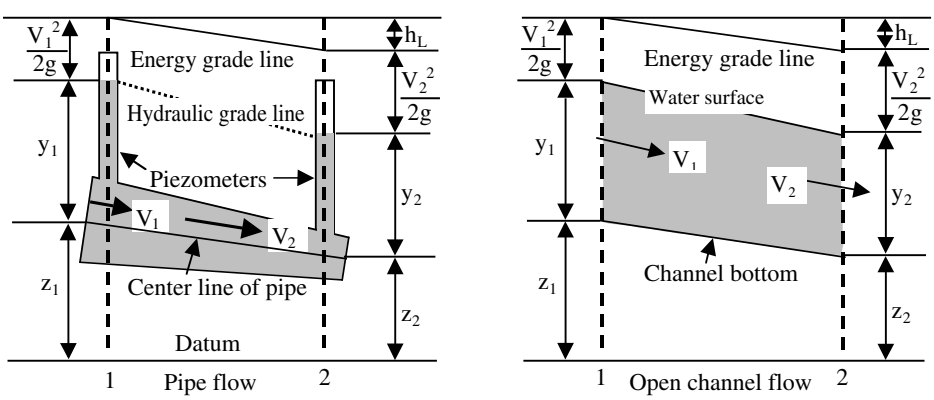

FIGURE 5.14 Comparison of pipe flow and open-channel flow. (Adapted from Metcalf & Eddy. Wastewater Engineering: Collection and Pumping of Wastewater, Tchobanoglous, G. (Ed.), McGraw-Hill, New York, 1981, p. 11.)

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Note: When water flows in an open channel, the HGL coincides with the profile of the water surface.

4. Energy grade line — the total energy of flow in any section with reference to some datum (i.e., a reference line, surface or point) is the sum of the elevation head, z, the pressure head, y, and the velocity head, $V^2/2g$. Figure 5.14 shows the energy grade line or energy gradient, which represents the energy from section to section. In the absence of frictional losses, the energy grade line remains horizontal, although the relative distribution of energy may vary between the elevation, pressure, and velocity heads. In all real systems, however, losses of energy occur because of resistance to flow, and the resulting energy grade line is sloped (i.e., the energy grade line is the slope of the specific energy line).
5. Specific energy (E) — sometimes called specific head, is the sum of the pressure head, y, and the velocity head, $V^2/2g$. The specific energy concept is especially useful in analyzing flow in open channels.
6. Steady flow — Occurs when the discharge or rate of flow at any cross section is constant.
7. Uniform and nonuniform flow — Uniform flow occurs when the depth, cross-sectional area, and other elements of flow are substantially constant from section to section. Nonuniform flow occurs when the slope, cross-sectional area, and velocity change from section to section. The flow through a venturi section used for measuring flow is a good example.
8. Varied flow — Flow in a channel is considered varied if the depth of flow changes along the length of the channel. The flow may be gradually varied or rapidly varied (i.e., when the depth of flow changes abruptly) as shown in Figure 5.15.
9. Slope (gradient) — The head loss per foot of channel.

5.10.3 Major Head Loss

Major head loss consists of pressure decreases along the length of pipe caused by friction created as water encounters the surfaces of the pipe. It typically accounts for most of the pressure drop in a pressurized or dynamic water system.

5.10.3.1 Components of Major Head Loss

The components that contribute to major head loss: roughness, length, diameter, and velocity.

5.10.3.1.1 Roughness

Even when new, the interior surfaces of pipes are rough. The roughness varies depending on pipe material, corrosion (tuberculation and pitting), and age. Because normal flow in a water pipe is turbulent, the turbulence increases with pipe roughness, which in turn causes pressure to drop over the length of the pipe.

5.10.3.1.2 Pipe Length

With every foot of pipe length, friction losses occur. The longer the pipe, the more head loss. Friction loss because of pipe length must be factored into head loss calculations.

5.10.3.1.3 Pipe Diameter

Generally, small diameter pipes have more head loss than large diameter pipes. This is the case because in large diameter pipes less of the water actually touches the interior surfaces of the pipe (encountering less friction) than in a small diameter pipe.

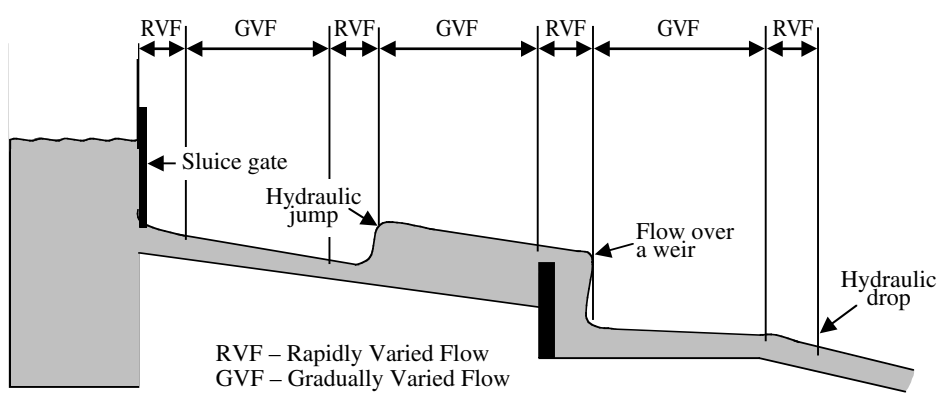

FIGURE 5.15 Varied flow. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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5.10.3.1.4 Water Velocity

Turbulence in a water pipe is directly proportional to the speed (or velocity) of the flow. Thus, the velocity head also contributes to head loss.

Note: For the same diameter pipe, when flow increases, head loss increases.

5.10.3.2 Calculating Major Head Loss

Henry Darcy, Julies Weisbach, and others developed the first practical equation used to determine pipe friction in about 1850. The equation or formula now known as the Darcy-Weisbach equation for circular pipes is:

$$h_f = f\frac{LV^2}{D2g} \tag{5.19}$$

In terms of the flow rate Q, the equation becomes:

$$h_f = \frac{8fLQ^2}{\pi^2 gD^5} \tag{5.20}$$

where

h_f = head loss (ft)
f = coefficient of friction
L = length of pipe (ft)
V = mean velocity (ft/sec)
D = diameter of pipe (ft)
g = acceleration due to gravity (32.2 ft/sec^2)
Q = flow rate (ft^3/sec)

The Darcy-Weisbach formula as such was meant to apply to the flow of any fluid. Into this friction factor was incorporated the degree of roughness and an element called the Reynold's number, which was based on the viscosity of the fluid and the degree of turbulence of flow.

The Darcy-Weisbach formula is used primarily for determining head loss calculations in pipes. For making this determination in open channels, the Manning equation was developed during the later part of the 19th century. Later, this equation was used for both open channels and closed conduits.

In the early 1900s, a more practical equation, the Hazen-Williams equation, was developed for use in making calculations related to water pipes and wastewater force mains:

$$Q = 0.435 \times CD^{2.63} \times S^{0.54} \tag{5.21}$$

where

Q = flow rate (ft^3/sec)
C = coefficient of roughness (C decreases with roughness)
D = hydraulic radius r (ft)
S = slope of energy grade line (ft/ft)

TABLE 5.3
***C* FACTORS**[15]

Type of Pipe	*C* Factor
Asbestos cement	140
Brass	140
Brick sewer	100
Cast iron	
10 years old	110
20 years old	90
Ductile iron (cement lined)	140
Concrete or concrete lined	
Smooth, steel forms	140
Wooden forms	120
Rough	110
Copper	140
Fire hose (rubber lined)	135
Galvanized iron	120
Glass	140
Lead	130
Masonry conduit	130
Plastic	150
Steel	
Coal-tar enamel lined	150
New unlined	140
Riveted	110
Tin	130
Vitrified	120
Wood stave	120

Source: From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.

5.10.3.2.1 C Factor

The *C* factor, as used in the Hazen-Williams formula, designates the coefficient of roughness. *C* does not vary appreciably with velocity, and by comparing pipe types and ages, it includes only the concept of roughness, ignoring fluid viscosity and Reynold's number.

Based on experience (experimentation), accepted tables of *C* factors have been established for pipe (see Table 5.3). Generally, *C* factor decreases by one with each year of pipe age. Flow for a newly designed system is often calculated with a *C* factor of 100, based on averaging it over the life of the pipe system.

Note: A high *C* factor means a smooth pipe. A low *C* factor means a rough pipe.

Note: An alternate to calculating the Hazen-Williams formula, called an alignment chart, has become quite popular for fieldwork. The alignment chart can be used with reasonable accuracy.

5.10.3.2.2 Slope

Slope is defined as the head loss per foot. In open channels, where the water flows by gravity, slope is the amount

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of incline of the pipe and is calculated as feet of drop per foot of pipe length (ft/ft). Slope is designed to be just enough to overcome frictional losses, so that the velocity remains constant, the water keeps flowing, and solids will not settle in the conduit. In piped systems, where pressure loss for every foot of pipe is experienced, slope is not provided by slanting the pipe, but instead by pressure added to overcome friction.

5.10.4 Minor Head Loss

In addition to the head loss caused by friction between the fluid and the pipe wall, losses also are caused by turbulence created by obstructions (i.e., valves and fittings of all types) in the line, changes in direction, and changes in flow area.

Note: In practice, if minor head loss is less than 5% of the total head loss, it is usually ignored.

5.11 BASIC PIPING HYDRAULICS

> Water, regardless of the source, is conveyed to the waterworks for treatment and distributed to the users. Conveyance from the source to the point of treatment occurs by aqueducts, pipelines, or open channels, but the treated water is normally distributed in pressurized closed conduits. After use, whatever the purpose, the water becomes wastewater, which must be disposed of somehow, but almost always ends up being conveyed back to a treatment facility before being outfalled to some water body, to begin the cycle again.
>
> We call this an urban water cycle, because it provides a human-generated imitation of the natural water cycle. Unlike the natural water cycle, however, without pipes, the cycle would be nonexistent or, at the very least, short-circuited.

For use as water mains in a distribution system, pipes must be strong and durable in order to resist applied forces and corrosion. The pipe is subjected to internal pressure from the water and to external pressure from the weight of the backfill (soil) and vehicles above it. The pipe may also have to withstand water hammer. Damage due to corrosion or rusting may also occur internally because of the water quality or externally because of the nature of the soil conditions.

Pipes used in a wastewater system must be strong and durable to resist the abrasive and corrosive properties of the wastewater. Like water pipes, wastewater pipes must also be able to withstand stresses caused by the soil backfill material and the effect of vehicles passing above the pipeline.

Joints between wastewater collection/interceptor pipe sections should be flexible, but tight enough to prevent excessive leakage, either of sewage out of the pipe or groundwater into the pipe.

Of course, pipes must be constructed to withstand the expected conditions of exposure, and pipe configuration systems for water distribution and/or wastewater collection and interceptor systems must be properly designed and installed in terms of water hydraulics. Because the water and wastewater operator should have a basic knowledge of water hydraulics related to commonly used standard piping configurations, piping basics are briefly discussed in this section.

5.11.1 Piping Networks

It would be far less costly and make for more efficient operation if municipal water and wastewater systems were built with separate single pipe networks extending from treatment plant to user's residence, or from user's sink or bathtub drain to the local wastewater treatment plant. Unfortunately, this ideal single-pipe scenario is not practical for real world applications. Instead of a single piping system, a network of pipes is laid under the streets. Each of these piping networks is composed of different materials that vary (sometimes considerably) in diameter, length, and age. These networks range in complexity to varying degrees, and each of these joined-together pipes contribute energy losses to the system.

5.11.1.1 Energy Losses in Pipe Networks

Water and wastewater flow networks may consist of pipes arranged in series, parallel, or some complicated combination. In any case, an evaluation of friction losses for the flows is based on energy conservation principles applied to the flow junction points. Methods of computation depend on the particular piping configuration. In general, however, they involve establishing a sufficient number of simultaneous equations or employing a friction loss formula where the friction coefficient depends only on the roughness of the pipe (e.g., Hazen-Williams equation). (Note: Demonstrating the procedure for making these complex computations is beyond the scope of this text. We only present the operator "need to know" aspects of complex or compound piping systems in this text.)

5.11.1.2 Pipes in Series

When two pipes of different sizes or roughnesses are connected in series (see Figure 5.16), head loss for a given discharge, or discharge for a given head loss, may be calculated by applying the appropriate equation between the bonding points, taking into account all losses in the interval. Thus, head losses are cumulative.

Series pipes may be treated as a single pipe of constant diameter to simplify the calculation of friction losses. The approach involves determining an equivalent length of a constant diameter pipe that has the same friction loss and discharge characteristics as the actual series pipe system.

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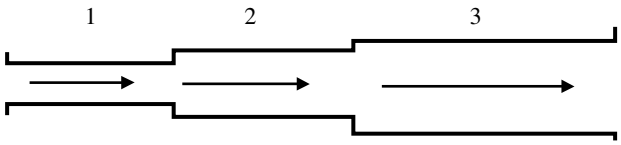

FIGURE 5.16 Pipes in series. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

In addition, application of the continuity equation to the solution allows the head loss to be expressed in terms of only one pipe size.

Note: In addition to the head loss caused by friction between the water and the pipe wall, losses also are caused by minor losses: obstructions in the line, changes in directions, and changes in flow area. In practice, the method of equivalent length is often used to determine these losses. The method of equivalent length uses a table to convert each valve or fitting into an equivalent length of straight pipe.

In making calculations involving pipes in series, remember these two important basic operational tenets:

1. The same flow passes through all pipes connected in series.
2. The total head loss is the sum of the head losses of all of the component pipes.

In some operations involving series networks where the flow is given and the total head loss is unknown, we can use the Hazen-Williams equation to solve for the slope and the head loss of each pipe as if they were separate pipes. Adding up the head losses to get the total head loss is then a simple matter.

Other series network calculations may not be as simple to solve using the Hazen-Williams equation. For example, one problem we may be faced with is what diameter to use with varying sized pipes connected together in a series combination. Moreover, head loss is applied to both pipes (and other multiples), and it is not known how much loss originates from each one. This makes determining slope difficult, but not impossible.

In such cases the equivalent pipe theory, as mentioned earlier, can be used. Again, one single equivalent pipe is created which will carry the correct flow. This is practical because the head loss through it is the same as that in the actual system. The equivalent pipe can have any C factor and diameter, just as long as those same dimensions are maintained all the way through to the end. Keep in mind that the equivalent pipe must have the correct length, so that it will allow the correct flow through, which yields the correct head loss (the given head loss).[16]

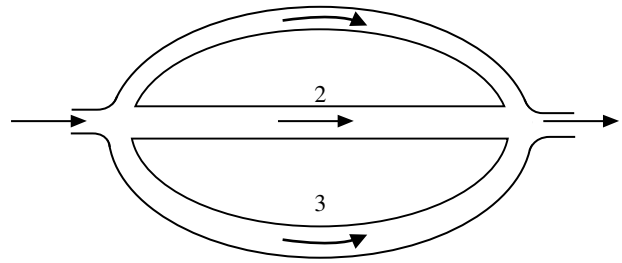

FIGURE 5.17 Pipe in parallel. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

5.11.1.3 Pipes in Parallel

Two or more pipes connected (as in Figure 5.17) so that flow is first divided among the pipes and is then rejoined comprise a parallel pipe system. A parallel pipe system is a common method for increasing the capacity of an existing line. Determining flows in pipes arranged in parallel are also made by application of energy conservation principles — specifically, energy losses through all pipes connecting common junction points must be equal. Each leg of the parallel network is treated as a series piping system and converted to a single equivalent length pipe. The friction losses through the equivalent length parallel pipes are then considered equal and the respective flows determined by proportional distribution.

Note: Computations used to determine friction losses in parallel combinations may be accomplished using a simultaneous solution approach for a parallel system that has only two branches. However, if the parallel system has three or more branches, a modified procedure using the Hazen-Williams loss formula is easier.[16]

5.12 OPEN-CHANNEL FLOW

Water is transported over long distances through aqueducts to locations where it is to be used and/or treated. Selection of an aqueduct type rests on such factors as topography, head availability, climate, construction practices, economics, and water quality protection. Along with pipes and tunnels, aqueducts may also include or be solely composed of open channels.[17]

In this section, we deal with water passage in open channels, which allow part of the water to be exposed to the atmosphere. This type of channel — an open-flow channel — includes natural waterways, canals, culverts, flumes, and pipes flowing under the influence of gravity.

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5.12.1 Characteristics of Open-Channel Flow[18]

Basic hydraulic principles apply in open-channel flow (with water depth constant) although there is no pressure to act as the driving force. Velocity head is the only natural energy this water possesses, and at normal water velocities, this is a small value ($V^2/2g$).

Several parameters can be (and often are) used to describe open-channel flow. However, we begin our discussion with a few characteristics, including laminar or turbulent; uniform or varied; and subcritical, critical, or supercritical.

5.12.1.1 Laminar and Turbulent Flow

Laminar and turbulent flow in open channels is analogous to that in closed pressurized conduits (i.e., pipes). It is important to point out that flow in open channels is usually turbulent. In addition, there is no important circumstance in which laminar flow occurs in open channels in either water or wastewater unit processes or structures.

5.12.1.2 Uniform and Varied Flow

Flow can be a function of time and location. If the flow quantity is invariant, it is said to be steady. *Uniform* flow is flow in which the depth, width, and velocity remain constant along a channel. This means that if the flow cross section does not depend on the location along the channel, the flow is said to be uniform. *Varied* or *nonuniform* flow involves a change in depth, width, and velocity, with a change in one producing a change in the others. Most circumstances of open-channel flow in water and wastewater systems involve varied flow. The concept of uniform flow is valuable, however, in that it defines a limit that the varied flow may be considered to be approaching in many cases.

Note: Uniform channel construction does not ensure uniform flow.

5.12.1.3 Critical Flow

Critical flow (i.e., flow at the critical depth and velocity) defines a state of flow between two flow regimes. Critical flow coincides with minimum specific energy for a given discharge and maximum discharge for a given specific energy. Critical flow occurs in flow measurement devices at or near free discharges, and establishes controls in open-channel flow. Critical flow occurs frequently in water and wastewater systems and is very important in their operation and design.

Note: Critical flow minimizes the specific energy and maximizes discharge.

5.12.1.4 Parameters Used in Open-Channel Flow

The three primary parameters used in open-channel flow are: hydraulic radius, hydraulic depth, and slope, S.

5.12.1.4.1 Hydraulic Radius

The hydraulic radius is the ratio of area in flow to wetted perimeter.

$$r_H = \frac{A}{P} \tag{5.22}$$

where

r_H = hydraulic radius
A = the cross sectional area of the water
P = wetted perimeter

Why is the hydraulic radius important?

Probably the best way in which to answer this question is by illustration. Consider, for example, that in open channels it is of primary importance to maintain the proper velocity. This is the case because if velocity is not maintained then flow stops (theoretically). In order to maintain velocity at a constant level, the channel slope must be adequate to overcome friction losses. As with other flows, calculation of head loss at a given flow is necessary, and the Hazen-Williams equation is useful (Equation 5.22). Keep in mind that the concept of slope has not changed. The difference? We are now measuring, or calculating for, the physical slope of a channel (ft/ft), equivalent to head loss.

The preceding seems logical, but there is a problem. The problem is with the diameter. In conduits that are not circular (grit chambers, contact basins, streams and rivers), or in pipes only partially full (drains, wastewater gravity mains, sewers, etc.) where the cross-sectional area of the water is not circular, there is no diameter.

If there is no diameter, then what do we do?

Because there is no diameter in a situation where the cross-sectional area of the water is not circular, we must use another parameter to designate the size of the cross section, and the amount of it that contacts the sides of the conduit. This is where the hydraulic radius (r_H) comes in. The hydraulic radius is a measure of the efficiency with which the conduit can transmit water. Its value depends on pipe size and amount of fullness. Simply, we use the hydraulic radius to measure how much of the water is in contact with the sides of the channel, or how much of the water is not in contact with the sides (see Figure 5.18).

Note: For a circular channel flowing either full or half-full, the hydraulic radius is D/4. Hydraulic radii of other channel shapes are easily calculated from the basic definition.

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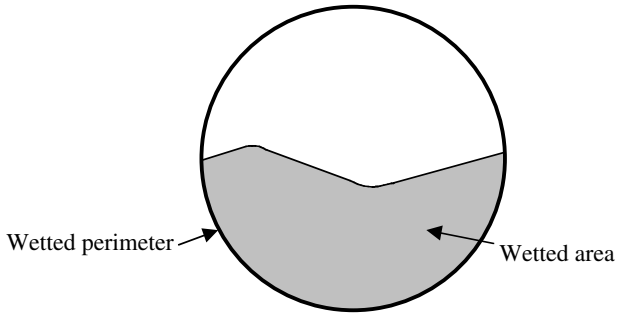

FIGURE 5.18 Hydraulic radius. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

5.12.1.4.2 ***Hydraulic Depth***

The hydraulic depth is the ratio of area in flow to the width of the channel at the fluid surface. [Note that another name for hydraulic depth is the hydraulic mean depth or hydraulic radius].

$$d_H = \frac{A}{w} \tag{5.23}$$

where

d_H = hydraulic depth
A = area in flow
w = width of the channel at the fluid surface

5.12.1.4.3 ***Slope***

The slope, S, in open channel equations is the slope of the energy line. If the flow is uniform, the slope of the energy line will parallel the water surface and channel bottom. In general, the slope can be calculated from Bernoulli's equation as the energy loss per unit length of channel.

$$S = \frac{Dh}{Dl} \tag{5.24}$$

5.12.2 Open-Channel Flow Calculations

As mentioned, the calculation for head loss at a given flow is typically accomplished by using Hazen-Williams equation. In addition, in open-channel flow problems where although the concept of slope has not changed, the problem arises with the diameter. Again, in pipes only partially full where the cross-sectional area of the water is not circular, there is no diameter. Thus, the hydraulic radius is used for these noncircular areas.

In the original version of the Hazen-Williams Equation, the hydraulic radius was incorporated. Moreover, similar versions developed by Antoine Chezy (pronounced "Shay-zee") and Robert Manning, and others incorporated the hydraulic radius. For use in open channels, Manning's formula has become most commonly used:

$$Q = \frac{1.5}{n} \times A \times r^{.66} \times S^{.5} \tag{5.25}$$

where

Q = channel discharge capacity (ft^3/sec)
1.5 = constant
n = channel roughness coefficient
A = cross-sectional flow area (ft^2)
r = hydraulic radius of the channel (ft)
S = slope of the channel bottom, dimensionless

The hydraulic radius of a channel is defined as the ratio of the flow area to the wetted perimeter *P*. In formula form, r = A/P. The new component is n (the roughness coefficient) and depends on the material and age for a pipe or lined channel and on topographic features for a natural streambed. It approximates roughness in open channels and can range from a value of 0.01 for a smooth clay pipe to 0.1 for a small natural stream. The value of n commonly assumed for concrete pipes or lined channels is 0.013. As the channels get smoother, n values decrease (see Table 5.4).

The following example illustrates the application of Manning's formula for a channel with a rectangular cross section.

Example 5.15

Problem:

A rectangular drainage channel is 3 ft wide and is lined with concrete, as illustrated in Figure 5.19. The bottom of the channel drops in elevation at a rate of 0.5/100 ft. What is the discharge in the channel when the depth of water is 2 ft?

Solution:

Assume n = 0.013

Referring to Figure 5.19, we see that the cross-sectional flow area A = 3 ft × 2 ft = 6 ft^2, and the wetted perimeter P = 2 ft + 3 ft + 2 ft = 7 ft. The hydraulic radius R = A/P = 6 ft^2/7 ft = 0.86 ft. The slope, S = 0.5/100 = 0.005.

Applying Manning's formula, we get:

$$Q = \frac{2.0}{0.013} \times 6 \times 0.86^{.66} \times 0.005^{.5}$$

$$Q = 59 \ ft^3/sec$$

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TABLE 5.4
Manning Roughness Coefficient (n)

Type of Conduit	n	Type of Conduit	n
		Pipe	
Cast iron, coated	0.012–0.014	Cast iron, uncoated	0.013–0.015
Wrought iron, galvanized	0.015–0.017	Wrought iron, black	0.012–0.015
Steel, riveted and spiral	0.015–0.017	Corrugated	0.021–0.026
Wood stave	0.012–0.013	Cement surface	0.010–0.013
Concrete	0.012–0.017	Vitrified	0.013–0.015
Clay, drainage tile	0.012–0.014		
		Lined Channels	
Metal, smooth semicircular	0.011–0.015	Metal, corrugated	0.023–0.025
Wood, planed	0.010–0.015	Wood, unplaned	0.011–0.015
Cement lined	0.010–0.013	Concrete	0.014–0.016
Cement rubble	0.017–0.030	Grass	N/R–0.020[a]
		Unlined Channels	
Earth: straight and uniform	0.017–0.025	Earth: dredged	0.025–0.033
Earth: winding	0.023–0.030	Earth: stony	0.025–0.040
Rock: smooth and uniform	0.025–0.035	Rock: jagged and irregular	0.035–0.045

[a] N/R = No result

Source: From Spellman, F.R. and Drinan, J., Water Hydraulics, Technomic Publ., Lancaster, PA, 2001.

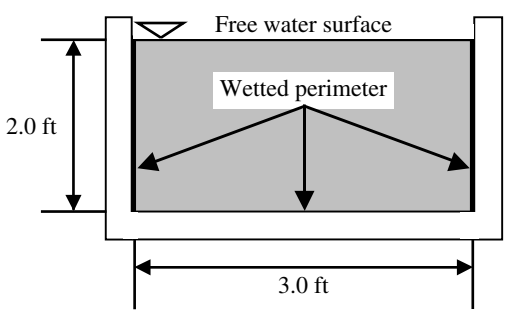

FIGURE 5.19 For Example 5.15. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

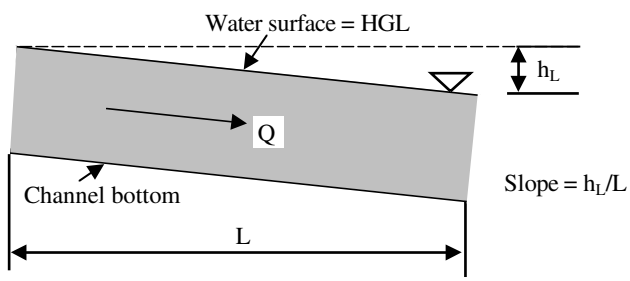

FIGURE 5.20 Steady uniform open-channel flow — where the slope of the water surface (or HGL) is equal to the slope of the channel bottom. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

5.12.3 Open-Channel Flow: The Bottom Line

To this point, we have set the stage for explaining (in the simplest possible way) what open-channel flow is and what it is all about. Now that we have explained the necessary foundational material and important concepts, we are ready to explain open-channel flow in a manner whereby it will be easily understood.

We stated that when water flows in a pipe or channel with a free surface exposed to the atmosphere, it is called open-channel flow. We also know that gravity provides the motive force, the constant push, while friction resists the motion and causes energy expenditure. River and stream flow is open-channel flow. Flow in sanitary sewers and storm water drains are open-channel flow, except in force mains where the water is pumped under pressure.

The key to solving storm water and/or sanitary sewer routine problems is a condition known as steady uniform flow; that is, we assume steady uniform flow. Steady flow means that the discharge is constant with time. Uniform flow means that the slope of the water surface and the cross-sectional flow area are also constant. It is common practice to call a length of channel, pipeline, or stream that has a relatively constant slope and cross section a reach.[19]

The slope of the water surface, under steady uniform flow conditions, is the same as the slope of the channel bottom. The HGL lies along the water surface and, as in pressure flow in pipes, the HGL slopes downward in the direction of flow. Energy loss is evident as the water surface elevation drops. Figure 5.20 illustrates a typical

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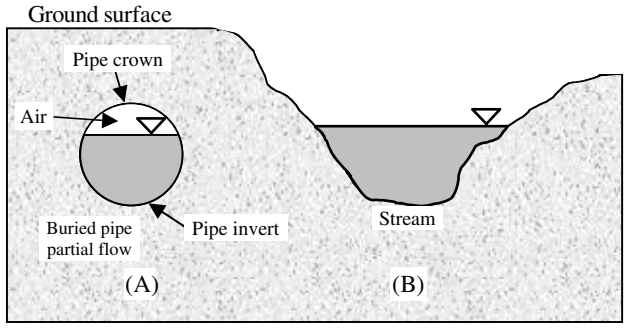

FIGURE 5.21 Shows open-channel flow, whether in a surface stream or in an underground pipe. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

profile view of uniform steady flow. The slope of the water surface represents the rate of energy loss.

Note: Rate of energy loss (see Figure 5.20) may be expressed as the ratio of the drop in elevation of the surface in the reach to the length of the reach.

Figure 5.21 shows typical cross sections of open-channel flow. In Figure 5.21A, the pipe is only partially filled with water and there is a free surface at atmospheric pressure. This is still open-channel flow, although the pipe is a closed underground conduit. Remember, the important point is that gravity — not a pump — is moving the water.

5.13 FLOW MEASUREMENT

> While it is clear that maintaining water/wastewater flow is at the heart of any treatment process, clearly, it is the measurement of flow that is essential to ensuring the proper operation of a water/wastewater treatment system. Few knowledgeable operators would argue with this statement. Hauser (1996) asks: "Why measure flow?" Then she explains: "The most vital activities in the operation of water and wastewater treatment plants are dependent on a knowledge of how much water is being processed."[20]

In the statement above, Hauser makes clear that flow measurement is not only important, but also routine, in water and wastewater operations. Routine, yes, but also the most important variable measured in a treatment plant. Hauser also pointed out that there are several reasons to measure flow in a treatment plant. The American Water Works Association[21] lists several additional reasons to measure flow:

1. The flow rate through the treatment processes needs to be controlled so that it matches distribution system use.
2. It is important to determine the proper feed rate of chemicals added in the processes.
3. The detention times through the treatment processes must be calculated. This is particularly applicable to surface water plants that must meet contact × time (C × T) values required by the Surface Water Treatment Rule.
4. Flow measurement allows operators to maintain a record of water furnished to the distribution system for periodic comparison with the total water metered to customers. This provides a measure of "water accounted for," or conversely (as pointed out earlier by Hauser), the amount of water wasted, leaked, or otherwise not paid for (i.e., lost water).
5. Flow measurement allows operators to determine the efficiency of pumps. (Note: Pumps are covered in detail in Chapter 7). Pumps that are not delivering their designed flow rate are probably not operating at maximum efficiency, and so power is being wasted.
6. For well systems, it is very important to maintain records of the volume of water pumped and the hours of operation for each well. The periodic computation of well pumping rates can identify problems such as worn pump impellers and blocked well screens.
7. Reports that must be furnished to the state by most water systems must include records of raw and finished water pumpage.
8. Wastewater generated by a treatment system must also be measured and recorded.
9. Individual meters are often required for the proper operation of individual pieces of equipment. For example, the makeup water to a fluoride saturator is always metered to assist in tracking the fluoride feed rate.

Note: Simply put, measurement of flow is essential for operation, process control, and recordkeeping of water and wastewater treatment plants.

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All of the uses addressed create the need for a number of flow-measuring devices, often with different capabilities. In this section, we discuss many of the major flow measuring devices currently used in water and wastewater operations.

5.13.1 Flow Measurement: The Old-Fashioned Way

An approximate but very simple method to determine open-channel flow has been used for many years. The procedure involves measuring the velocity of a floating object moving in a straight uniform reach of the channel or stream. If the cross-sectional dimensions of the channel are known and the depth of flow is measured, then flow area can be computed. From the relationship $Q = A \times V$, the discharge Q can be estimated.

In preliminary fieldwork, this simple procedure is useful in obtaining a ballpark estimate for the flow rate, but is not suitable for routine measurements.

Example 5.16

Problem:

A floating object is placed on the surface of water flowing in a drainage ditch and is observed to travel a distance of 20 m downstream in 30 sec. The ditch is 2 m wide and the average depth of flow is estimated to be 0.5 m. Estimate the discharge under these conditions.

Solution:

The flow velocity is computed as distance over time:

$$V = \frac{D}{t} = \frac{20\ \text{m}}{30\ \text{s}} = 0.67\ \text{m/sec}$$

The channel area is:

$$A = 2\ \text{m} \times 0.5\ \text{m} = 1.0\ \text{m}^2$$

The discharge is:

$$Q = A \times V = 1.0\ \text{m}^2 \times 0.66\ \text{m}^2 = 0.66\ \text{m}^3/\text{sec}$$

5.13.2 Basis of Traditional Flow Measurement

Flow measurement can be based on flow rate, or flow amount. Flow rate is measured in gallons per minute, million gallons per day, or cubic feet per second. Water and wastewater operations need flow rate meters to determine process variables within the treatment plant, in wastewater collection, and in potable water distribution. Typically, flow rate meters used are differential pressure meters, magnetic meters, and ultrasonic meters. Flow rate meters are designed for metering flow in closed pipe or open-channel flow.

Flow amount is measured in either gallons or in cubic feet. Typically, a totalizer, which sums up the gallons or cubic feet that pass through the meter, is used. Most service meters are of this type. They are used in private, commercial, and industrial activities where the total amount of flow measured is used in determining customer billing. In wastewater treatment, where sampling operations are important, automatic composite sampling units — flow proportioned to grab a sample every so many gallons — are used. Totalizer meters can be the velocity (propeller or turbine), positive displacement, or compound types. In addition, weirs and flumes are used extensively for measuring flow in wastewater treatment plants because they are not affected (to a degree) by dirty water or floating solids.

5.13.3 Flow Measuring Devices

In recent decades, flow measurement technology has evolved rapidly from the old fashioned way of measuring flow we discussed in Section 5.13.1, to the use of simple practical measuring devices, and finally to much more sophisticated devices. Physical phenomena discovered centuries ago have been the starting point for many of the viable flowmeter designs used today. Moreover, the recent technology explosion has enabled flowmeters to handle many more applications than could have been imagined centuries ago.

Before selecting a particular type of flow measurement device, Kawamura[22] recommends consideration of several questions.

1. Is liquid or gas flow being measured?
2. Is the flow occurring in a pipe or in an open channel?
3. What is the magnitude of the flow rate?
4. What is the range of flow variation?
5. Is the liquid being measured clean, or does it contain suspended solids or air bubbles?
6. What is the accuracy requirement?
7. What is the allowable head loss by the flowmeter?
8. Is the flow corrosive?
9. What types of flowmeters are available to the region?
10. What types of postinstallation service are available to the area?

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5.13.3.1 Differential Pressure Flowmeters[23]

For many years differential pressure flowmeters have been the most widely applied flow-measuring device for water flow in pipes that require accurate measurement at reasonable cost. The differential pressure type of flowmeter makes up the largest segment of the total flow measurement devices currently being used. Differential pressure-producing meters currently on the market are the venturi, Dall type, Hershel venturi, universal venturi, and venturi inserts.

The differential pressure-producing device has a flow restriction in the line that causes a differential pressure or head to be developed between the two measurement locations. Differential pressure flowmeters are also known as head meters, and, of all the head meters, the orifice flowmeter is the most widely applied device.

The advantages of differential pressure flowmeters include:

1. Simple construction
2. Relatively inexpensive
3. No moving parts
4. Transmitting instruments are external
5. Low maintenance
6. Wide application of flowing fluid that is suitable for measuring both gas and liquid flow
7. Ease of instrument and range selection
8. Extensive product experience and performance database

The disadvantages include:

1. Flow rate is a nonlinear function of the differential pressure.
2. There is a low flow rate range with normal instrumentation.

5.13.3.1.1 Operating Principle

Differential pressure flowmeters operate on the principle of measuring pressure at two points in the flow, which provides an indication of the rate of flow that is passing by. The difference in pressures between the two measurement locations of the flowmeter is the result of the change in flow velocities. Simply, there is a set relationship between the flow rate and volume, so the meter instrumentation automatically translates the differential pressure into a volume of flow. The volume of flow rate through the cross-sectional area is given by

$$Q = A \times V(\text{average})$$

where

Q = the volumetric flow rate
A = flow in the cross-sectional area
V = the average fluid velocity

5.13.3.1.2 Types of Differential Pressure Flowmeters

Differential pressure flowmeters operate on the principle of developing a differential pressure across a restriction that can be related to the fluid flow rate.

Note: Optimum measurement accuracy is maintained when the flowmeter is calibrated, the flowmeter is installed in accordance with standards and codes of practice, and the transmitting instruments are periodically calibrated.

The most commonly used differential pressure flowmeter types used in water and wastewater treatment are:

1. Orifice
2. Venturi
3. Nozzle
4. Pitot-static tube

5.13.3.1.2.1 Orifice

The most commonly applied orifice is a thin, concentric, and flat metal plate with an opening in the plate (see Figure 5.22) that is installed perpendicular to the flowing stream in a circular conduit or pipe. Typically, a sharp-edged hole is bored in the center of the orifice plate. As the flowing water passes through the orifice, the restriction causes an increase in velocity. A concurrent decrease in pressure occurs as potential energy (static pressure) is converted into kinetic energy (velocity). As the water leaves the orifice, its velocity decreases and its pressure increases as kinetic energy is converted back into potential energy according to the laws of conservation of energy. However, there is always some permanent pressure loss due to friction, and the loss is a function of the ratio of the diameter of the orifice bore (d) to the pipe diameter (D).

For dirty water applications (i.e., wastewater), a concentric orifice plate will eventually have impaired performance due to dirt buildup at the plate. Instead, eccentric

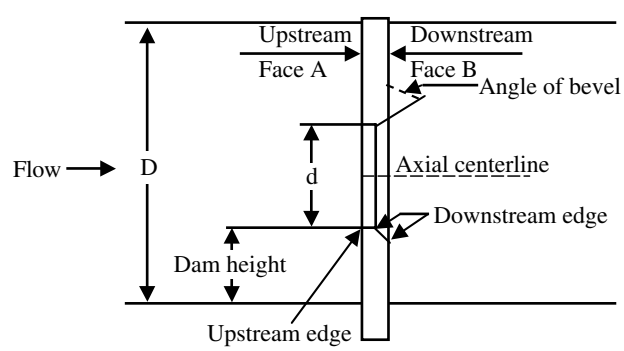

FIGURE 5.22 Orifice plate. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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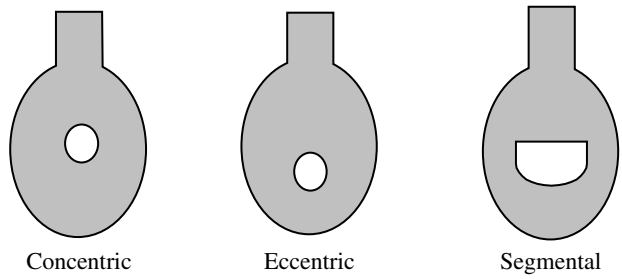

FIGURE 5.23 Types of orifice plates. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

or segmental orifice plates (see Figure 5.23) are often used. Measurements are typically less accurate than those obtained from the concentric orifice plate. Eccentric or segmental orifices are rarely applied in current practice.

The orifice differential pressure flowmeter is the lowest cost differential flowmeter, is easy to install, and has no moving parts. However, it also has high permanent head loss (ranging from 40 to 90%) higher pumping costs, an accuracy of ±2% for a flow range of 4:1, and is affected with wear or damage.

Note: Orifice meters are not recommended for permanent installation to measure wastewater flow; solids in the water easily catch on the orifice, throwing off accuracy. For installation, it is necessary to have 10 diameters of straight pipe ahead of the orifice meter to create a smooth flow pattern, and 5 diameters of straight pipe on the discharge side.

5.13.3.1.2.2 Venturi

A venturi is a restriction with a relatively long passage with smooth entry and exit (see Figure 5.24). It has long life expectancy, simplicity of construction, and relatively high-pressure recovery (i.e., produces less permanent pressure loss than a similar sized orifice). Despite these advantages, the venturi is more expensive, is not linear with flow rate, and is the largest and heaviest differential pressure flowmeter. It is often used in wastewater flows since the smooth entry allows foreign material to be swept through instead of building up as it would in front of an orifice. The accuracy of this type flowmeter is ±1% for a flow range of 10:1. The head loss across a venturi flowmeter is relatively small. It ranges from 3 to 10% of the differential, depending on the ratio of the throat diameter to the inlet diameter (also known as beta ratio).

5.13.3.1.2.3 Nozzle

Flow nozzles (flow tubes) have a smooth entry and sharp exit (see Figure 5.24). For the same differential pressure, the permanent pressure loss of a nozzle is of the same order as that of an orifice, but it can handle wastewater

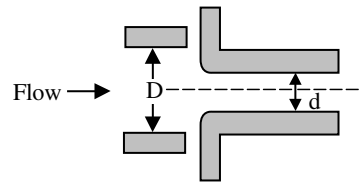

FIGURE 5.24 Long radius flow nozzle. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

and abrasive fluids better than an orifice. Note that for the same line size and flow rate, the differential pressure at the nozzle is lower (head loss ranges from 10 to 20% of the differential) than the differential pressure for an orifice; hence, the total pressure loss is lower than an orifice's. Nozzles are primarily used in steam service because of their rigidity, which makes them dimensionally more stable at high temperatures and velocities than orifices.

Note: A useful characteristic of nozzles it that they reach a critical flow condition — a point at which further reduction in downstream pressure does not produce a greater velocity through the nozzle. When operated in this mode, nozzles are very predictable and repeatable.

5.13.3.1.2.4 Pitot Tube

A Pitot tube is a point velocity-measuring device (see Figure 5.25). It has an impact port; as fluid hits the port, its velocity is reduced to zero and kinetic energy (velocity) is converted to potential energy (pressure head). The pressure at the impact port is the sum of the static pressure and the velocity head. The pressure at the impact port is also known as stagnation pressure or total pressure. The pressure difference between the impact pressure and the static pressure measured at the same point is the velocity head. The flow rate is the product of the measured velocity and the cross-sectional area at the point of measurement. Note that the Pitot tube has negligible permanent pressure drop in the line, but the impact port must be located in

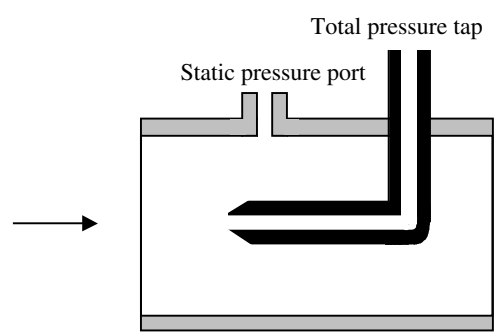

FIGURE 5.25 Pitot tube. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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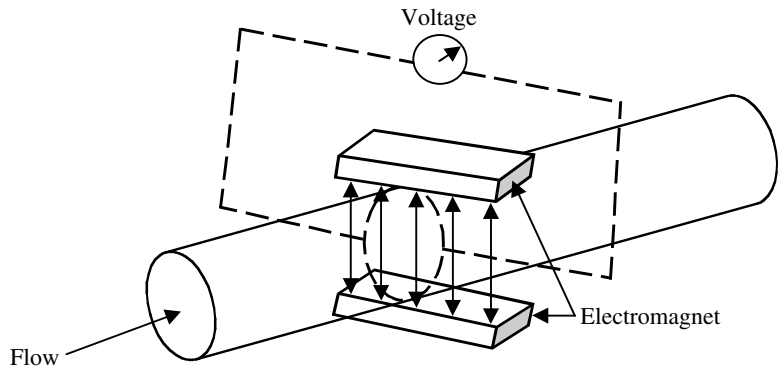

FIGURE 5.26 Magnetic flowmeter. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

the pipe where the measured velocity is equal to the average velocity of the flowing water through the cross section.

5.13.3.2 Magnetic Flowmeters[24]

Magnetic flowmeters are relatively new to the water and wastewater industry. They are volumetric flow devices designed to measure the flow of electrically conductive liquids in a closed pipe. They measure the flow rate based on the voltage created between two electrodes (in accordance with Faraday's law of electromagnetic induction) as the water passes through an electromagnetic field (see Figure 5.26). Induced voltage is proportional to flow rate. Voltage depends on magnetic field strength (constant), distance between electrodes (constant), and velocity of flowing water (variable).

Properties of the magnetic flowmeter include:

1. Minimal head loss (no obstruction with line size meter)
2. No effect on flow profile
3. Suitablity for size range between 0.1 in. to 120 in.
4. An accuracy rating of from 0.5 to 2% of flow rate
5. Ability to measure forward or reverse flow.

The advantages of magnetic flowmeters include:

1. No obstruction to flow
2. Minimal head loss
3. Wide range of sizes
4. Bidirectional flow measurement
5. Variations in density, viscosity, pressure, and temperature yield negligible effect.
6. Wastewater use
7. No moving parts

The disadvantages include:

1. Its metered liquid must be conductive (but you would not use this type meter on clean fluids anyway).
2. It is bulky, expensive in smaller sizes, and may require periodic calibration to correct drifting of the signal.

The combination of the magnetic flowmeter and the transmitter is considered as a system. A typical system, schematically illustrated in Figure 5.27, shows a transmitter mounted remote from the magnetic flowmeter. Some systems are available with transmitters mounted integral to the magnetic flowmeter. Each device is individually calibrated during the manufacturing process, and the accuracy statement of the magnetic flowmeter includes both pieces of equipment. One is not sold or used without the other.

It is also interesting to note that since 1983 almost every manufacturer now offers the microprocessor-based transmitter.

Regarding minimum piping straight run requirements, magnetic flowmeters are quite forgiving of piping configuration. The downstream side of the magnetic flowmeter is much less critical than the upstream side. Essentially,

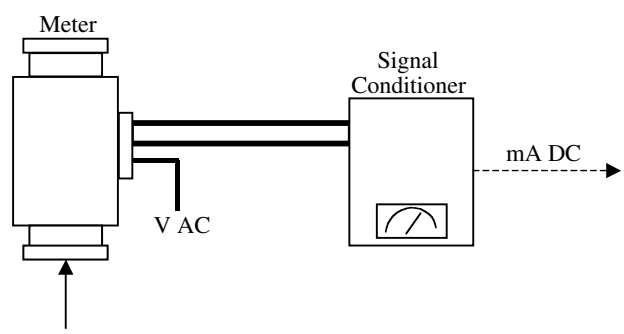

FIGURE 5.27 Magnetic flowmeter system. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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all that is required of the downstream side is that sufficient backpressure is provided to keep the magnetic flowmeter full of liquid during flow measurement. Two diameters downstream should be acceptable.[25]

Note: Magnetic flowmeters are designed to measure conductive liquids only. If air or gas is mixed with the liquid, the output becomes unpredictable.

5.13.3.3 Ultrasonic Flowmeters

Ultrasonic flowmeters use an electronic transducer to send a beam of ultrasonic sound waves through the water to another transducer on the opposite side of the unit. The velocity of the sound beam varies with the liquid flow rate, so the beam can be electronically translated to indicate flow volume. The accuracy is ±1% for a flow velocity ranging from 1 to 25 ft/s, but the meter reading is greatly affected by a change in the fluid composition

Two types of ultrasonic flowmeters are in general use for closed pipe flow measurements. The first (time of flight or transit time) usually uses pulse transmission and is for clean liquids, while the second (Doppler) usually uses continuous wave transmission and is for dirty liquids.

5.13.3.3.1 Time of Flight Ultrasonic Flowmeters[26]

Time-of-flight flowmeters make use of the difference in the time for a sonic pulse to travel a fixed distance, first in the direction of flow and then against the flow. This is accomplished by opposing transceivers positioned on diagonal path across meter spool as shown in Figure 5.28. Each transmits and receives ultrasonic pulses with flow and against flow. The fluid velocity is directly proportional to time difference of pulse travel.

The time of flight ultrasonic flowmeter operates with minimal head loss, has an accuracy range of 1 to 2.5% full scale, and can be mounted as integral spool piece transducers or as externally mountable clamp-ons. They can measure flow accurately when properly installed and applied.

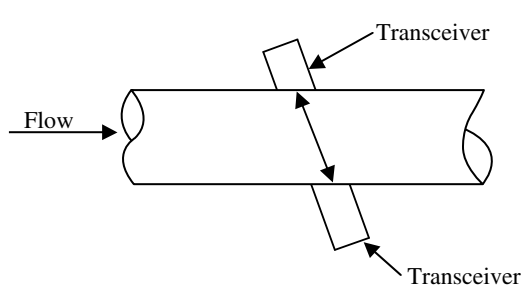

FIGURE 5.28 Time-of-flight ultrasonic flowmeter. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

The advantages of time-of-flight ultrasonic flowmeters include:

1. No obstruction to flow
2. Minimal head loss
3. Clamp-ons
   a. Can be portable
   b. No interruption of flow
4. No moving parts
5. Linear over wide range
6. Wide range of pipe sizes
7. Bidirectional flow measurement

The disadvantages include:

1. Sensitivity to solids or bubble content
   a. Interference with sound pulses
2. Sensitivity to flow disturbances
3. Alignment of transducers is critical
4. Clamp-on — pipe walls must freely pass ultrasonic pulses

5.13.3.3.2 Doppler Type Ultrasonic Flowmeters

Doppler ultrasonic flowmeters make use of the Doppler frequency shift caused by sound scattered or reflected from moving particles in the flow path. Doppler meters are not considered to be as accurate as time of flight flowmeters. However, they are very convenient to use and generally more popular and less expensive than time of flight flowmeters.

In operation, a propagated ultrasonic beam is interrupted by particles in moving fluid and reflected toward a receiver. The difference of propagated and reflected frequencies is directly proportional to fluid flow rate.

Ultrasonic Doppler flowmeters feature minimal head loss with an accuracy of 2% to 5% full scale. They are either of the integral spool piece transducer type or externally mountable clamp-ons.

The advantages of the Doppler ultrasonic flowmeter includes:

1. No obstruction to flow
2. Minimal head loss
3. Clamp-ons
   a. Can be portable
   b. No interruption of flow
4. No moving parts
5. Linear over wide range
6. Wide range of pipe sizes
7. Low installation and operating costs
8. Bidirectional flow measurement

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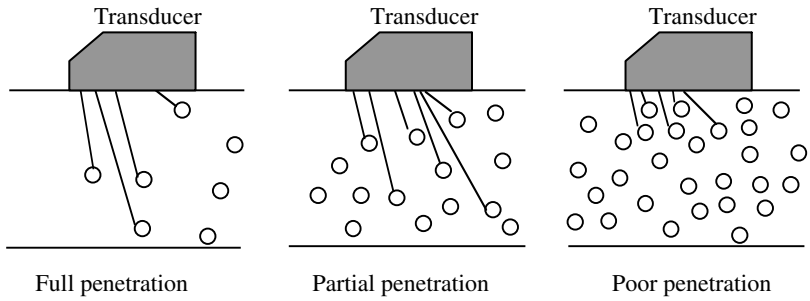

FIGURE 5.29 Particle concentration effect. The more particles there are the more error. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

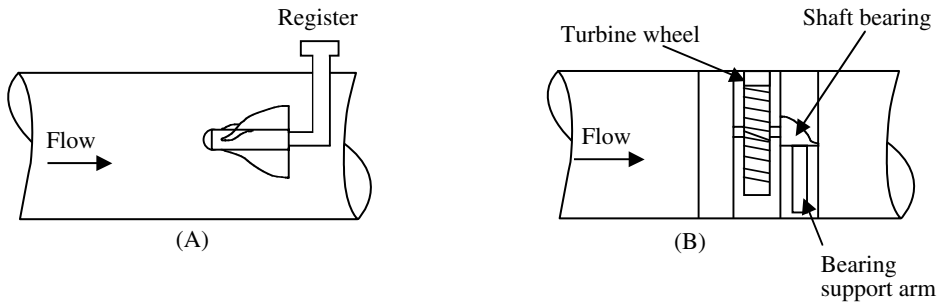

FIGURE 5.30 (A) Propeller meter; (B) turbine meter. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

The disadvantages include:

1. Minimum concentration and size of solids or bubbles for reliable operation required (see Figure 5.29)
2. Minimum speed to maintain suspension required
3. Clamp-on type limited to sonically conductive pipe

5.13.3.4 Velocity Flowmeters[27]

Velocity or turbine flowmeters use a propeller or turbine to measure the velocity of the flow passing the device (see Figure 5.30). The velocity is then translated into a volumetric amount by the meter register. Sizes exist from a variety of manufacturers to cover the flow range from 0.001 gal/min to over 25,000 gal/min for liquid service. End connections are available to meet the various piping systems. The flowmeters are typically manufactured of stainless steel but are also available in a wide variety of materials, including plastic. Velocity meters are applicable to all clean fluids. Velocity meters are particularly well suited for measuring intermediate flow rates on clean water.

The advantages of the velocity meter include:

1. High accuracy
2. Corrosion-resistant materials
3. Long-term stability
4. Liquid or gas operation
5. Wide operating range
6. Low pressure drop
7. Wide temperature and pressure limits
8. High shock capability
9. Wide variety of electronics available

As shown in Figure 5.30, a turbine flowmeter consists of a rotor mounted on a bearing and shaft in a housing. The fluid to be measured is passed through the housing, causing the rotor to spin with a rotational speed proportional to the velocity of the flowing fluid within the meter. A device to measure the speed of the rotor is employed to make the actual flow measurement. The sensor can be a mechanically gear-driven shaft to a meter or an electronic sensor that detects the passage of each rotor blade generating a pulse. The rotational speed of the sensor shaft and the frequency of the pulse are proportional to the volumetric flow rate through the meter.

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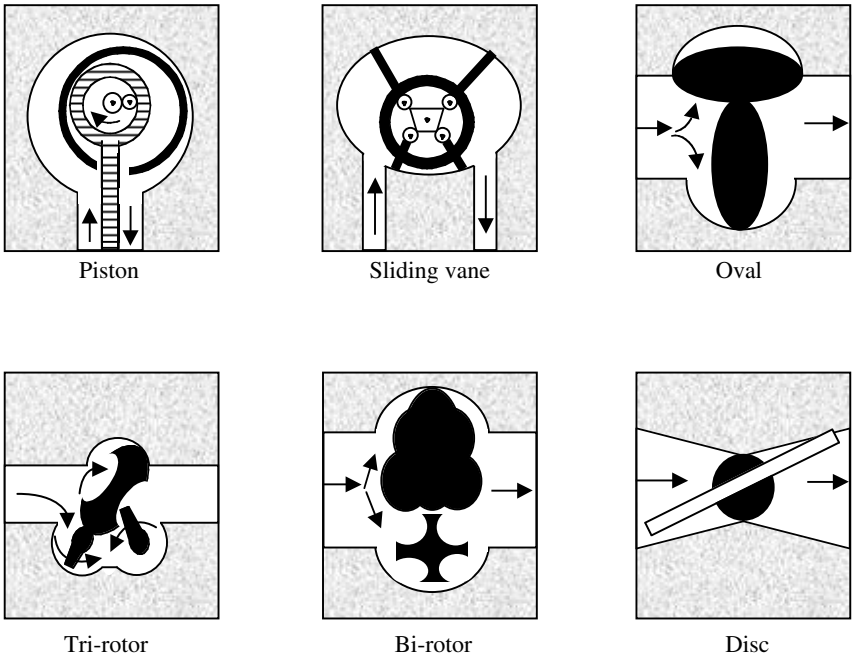

FIGURE 5.31 Six common positive displacement meter principles. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

5.13.3.5 Positive-Displacement Flowmeters[28]

Positive-displacement flowmeters are most commonly used for customer metering; they have long been used to measure liquid products. These meters are very reliable and accurate for low flow rates because they measure the exact quantity of water passing through them. Positive-displacement flowmeters are frequently used for measuring small flows in a treatment plant because of their accuracy. Repair or replacement is easy since they are so common in the distribution system.

In essence, a positive-displacement flowmeter is a hydraulic motor with high volumetric efficiency that absorbs a small amount of energy from the flowing stream. This energy is used to overcome internal friction in driving the flowmeter and its accessories and is reflected as a pressure drop across the flowmeter. Pressure drop is regarded as unavoidable but must be minimized. It is the pressure drop across the internals of a positive displacement flowmeter that actually creates a hydraulically unbalanced rotor, which causes rotation.

A positive-displacement flowmeter continuously divides the flowing stream into known volumetric segments, isolates the segments momentarily, and returns them to the flowing stream while counting the number of displacements. A positive-displacement flowmeter can be broken down into three basic components: the external housing, the measuring unit, and the counter drive train.

The external housing is the pressure vessel that contains the product being measured. The measuring unit is a precision metering element and is made up of the measuring chamber and the displacement mechanism. The most common displacement mechanisms include the oscillating piston, sliding vane, oval gear, tri-rotor, bi-rotor, and nutating disc types (see Figure 5.31). The counter drivetrain is used to transmit the internal motion of the measuring unit into a usable output signal. Many positive-displacement flowmeters use a mechanical gear train that requires a rotary shaft seal or packing gland where the shaft penetrates the external housing.

The positive-displacement flowmeter can offer excellent accuracy, repeatability, and reliability in many applications. It has satisfied many needs in the past and should play a vital role in serving the future needs as required.

5.13.4 Open-Channel Flow Measurement[29]

The majority of industrial liquid flows are carried in closed conduits that flow completely full and under pressure. However, this is not the case for high volume flows of liquids in waterworks, sanitary, and stormwater systems that are commonly carried in open channels. Low system heads and high volumetric flow rates characterize flow in open-channels.

The most commonly used method of measuring the rate of flow in open-channel flow configurations is that of hydraulic structures. In this method, flow in an open channel is measured by inserting a hydraulic structure into the channel, which changes the level of liquid in or near the structure. By selecting the shape and dimensions of the hydraulic structure, the rate of flow through or over the

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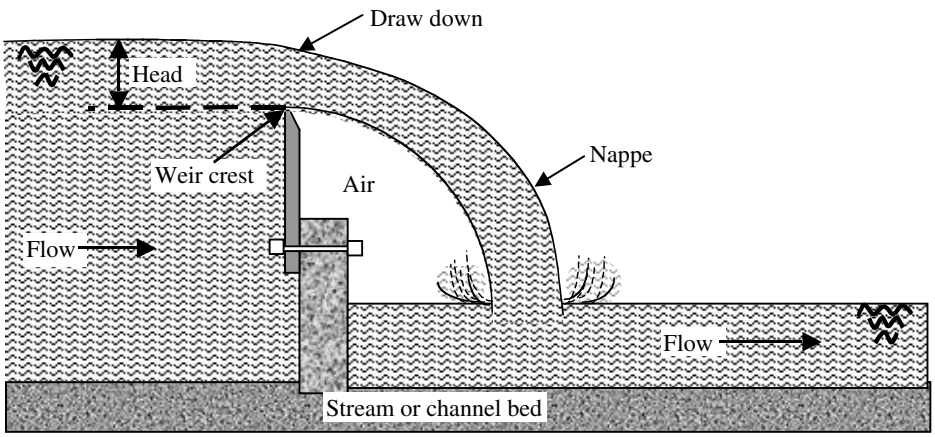

FIGURE 5.32 Side view of a weir. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

restriction will be related to the liquid level in a known manner. Thus, the flow rate through the open channel can be derived from a single measurement of the liquid level in or near the structure.

The hydraulic structures used in measuring flow in open channels are known as primary measuring devices. They may be divided into two broad categories, weirs and flumes and are covered in the following subsections.

5.13.4.1 Weirs

The weir is a widely used device to measure open-channel flow. As can be seen in Figure 5.32, a weir is simply a dam or obstruction placed in the channel so that water backs up behind it and then flows over it. The sharp crest or edge allows the water to spring clear of the weir plate and to fall freely in the form of a nappe.

As Nathanson[30] points out, when the nappe discharges freely into the air, there is a hydraulic relationship between the height and depth of water flowing over the weir crest and the flow rate. This height, the vertical distance between the crest and the water surface, is called the head on the weir; it can be measured directly with a meter or yardstick or automatically by float-operated recording devices. Two common weirs, rectangular and triangular, are shown in Figure 5.33.

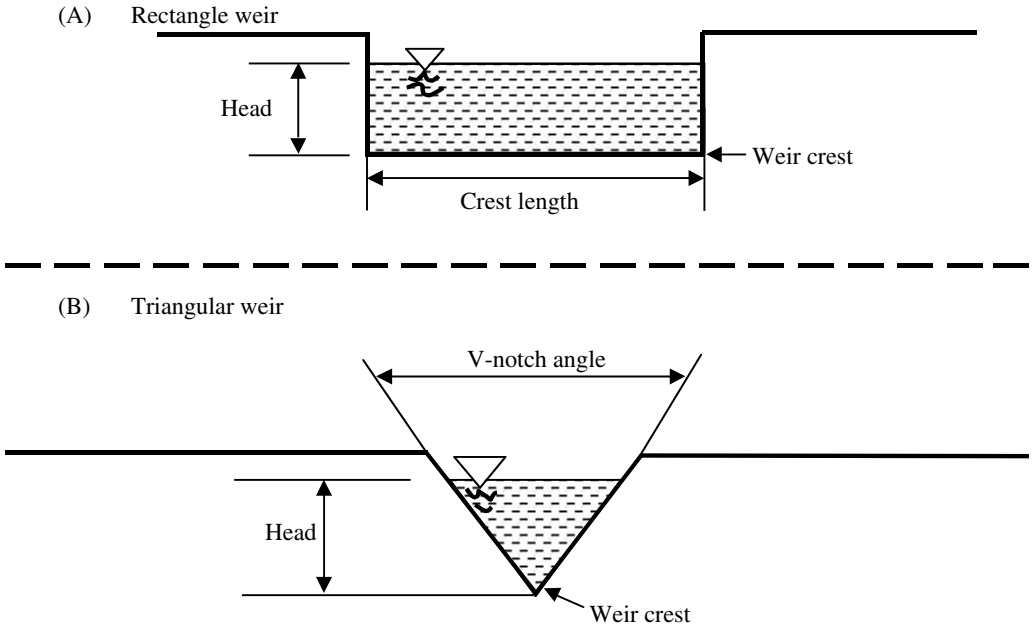

FIGURE 5.33 (A) Rectangular weir; (B) triangular V-notch weir. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

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Rectangular weirs are commonly used for large flows (see Figure 5.33A). The formula used to make rectangular weir computations is:

$$Q = 3.33 \times L \times h^{1.5} \qquad (5.26)$$

where

Q = flow
L = width of weir
h = head on weir (measured from edge of weir in contact with the water, up to the water surface).

Example 5.17

Problem:

A 4-ft high weir extends 15 ft across a rectangular channel in which there are 80 ft^3/sec flowing. What is the depth just upstream from the weir?

Solution:

$Q = 3.33 \times L \times h^{1.5}$
$80 = 3.33 \times 15\ h^{1.5}$
h = 1.4 ft (w/calculator: 1.6 INV $y^{x1.5}$ = 1.36 or 1.4)
4 ft height of weir + 1.4 ft head of water = 5.4 ft depth

Triangular weirs, also called V-notch weirs, can have notch angles ranging from 22.5° to 90°, but right angle notches are the most common (see Figure 5.33B).

The formula used to make V-notch (90°) weir calculations is

$$Q = 2.5 \times h^{2.5}$$

where

Q = flow
h = head on weir (measured from bottom of notch to water surface)

Example 5.18

Problem:

What should be the minimum weir height for measuring a flow of 1200 gal/min with a 90° V-notch weir, if the flow is mow moving at 4 ft/sec in a 2.5 ft wide rectangular channel?

Solution:

$$\frac{1200\ \text{gpm}}{60\ \text{sec/min} \times 7.48\ \text{gal/ft}^3} = 2.67\ \text{ft}^3/\text{sec}$$

$Q = A \times V$
$2.67 = 2.5 \times d \times 4$
d = 0.27 ft
$Q = 2.5 \times h^{2.5}$
$2.67 = 2.5 \times h^{2.5}$
h = 1.03 (calculator: 1.06 INV $y^{x2.5}$ = 1.026 or 1.03)
0.27 ft (original depth) + 1.03 (head on weir) = 1.3 ft

It is important to point out that weirs, aside from being operated within their flow limits, must also be operated within the available system head. In addition, the operation of the weir is sensitive to the approach velocity of the water, often necessitating a stilling basin or pound upstream of the weir. Weirs are not suitable for water that carries excessive solid materials or silt, which deposit in the approach channel behind the weir and destroy the conditions required for accurate discharge measurements.

Note: Accurate flow rate measurements with a weir cannot be expected unless the proper conditions and dimensions are maintained.

5.13.4.2 Flumes

A flume is a specially shaped constricted section in an open channel (similar to the venturi tube in a pressure conduit). The special shape of the flume (see Figure 5.34) restricts the channel area and/or changes the channel slope, resulting in an increased velocity and a change in the level of the liquid flowing through the flume. The flume restricts the flow, and then expands it in a definite fashion. The flow rate through the flume may be determined by measuring the head on the flume at a single point, usually at some distance downstream from the inlet.

Flumes can be categorized as belonging to one of three general families, depending upon the state of flow induced — subcritical, critical, or supercritical. Typically, flumes that induce a critical or supercritical state of flow are most commonly used. This is because when critical or supercritical flow occurs in a channel, one head measurement can indicate the discharge rate if it is made far enough upstream so that the flow depth is not affected by the drawdown of the water surface as it achieves or passes through a critical state of flow. For critical or supercritical states of flow, a definitive head-discharge relationship can be established and measured based on a single head reading. Thus, most commonly encountered flumes are designed to pass the flow from subcritical through critical or near the point of measurement.

The most common flume used for a permanent wastewater flowmetering installation is called the Parshall flume, shown in Figure 5.34.

Formulas for flow through Parshall flumes differ, dependent on throat width. The formula below can be used for widths of 1 to 8 feet, and applies to a medium range of flows.

$$Q = 4 \times W \times H_a^{1.52} \times W^{.026} \qquad (5.27)$$

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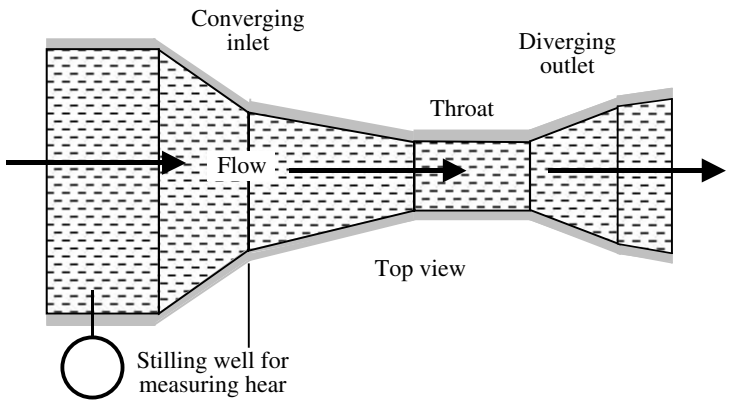

FIGURE 5.34 Parshall flume. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

where

Q = flow
H_a = depth in stilling well upstream
W = width of throat

Note: Parshall flumes are low maintenance items.

5.14 CHAPTER REVIEW QUESTIONS AND PROBLEMS

5.1. What should be the minimum weir height for measuring a flow of 900 gal/min with a 90° V-notch weir, if the flow is now moving at 3 ft/sec in a 2-ft wide rectangular channel?

5.2. A 90° V-notch weir is to be installed in a 30-in. diameter sewer to measure 600 gal/min. What head should be expected?

5.3. For dirty water operations, a _____ or _____ orifice plate should be used.

5.4. A _____ has a smooth entry and sharp exit.

5.5. A _____ sends a beam of ultrasonic sound waves through the water to another transducer on the opposite side of the unit.

5.6. Find the number of gallons in a storage tank that has a volume of 660 $ft.^3$

5.7. Suppose a rock weighs 160 lb in air and 125 lb underwater. What is the specific gravity?

5.8. A 110-ft diameter cylindrical tank contains 1.6 MG H_2O. What is the water depth?

5.9. The pressure in a pipeline is 6400 psf. What is the head on the pipe?

5.10. The pressure on a surface is 35 psi gauge. If the surface area is 1.6 ft^2, what is the force (lb) exerted on the surface?

5.11. Bernoulli's principle states that the total energy of a hydraulic fluid is _____ _____.

5.12. What is pressure head?

5.13. What is a hydraulic grade line?

5.14. A flow of 1500 gal/min takes place in a 12-in. pipe. Calculate the velocity head.

5.15. Water flows at 5.00 mL/sec in a 4-in. line under a pressure of 110 psi. What is the pressure head (ft H_2O)?

5.16. In Question 5.15, what is the velocity head in the line?

5.17. What is velocity head in a 6-in. pipe connected to a 1-ft pipe, if the flow in the larger pipe is 1.46 ft^3/sec?

5.18. What is velocity head?

5.19. What is suction lift?

5.20. Explain energy grade line.

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6 Fundamentals of Electricity

We believe that electricity exists, because the electric company keeps sending us bills for it, but we cannot figure out how it travels inside wires.

Dave Barry

When Gladstone was British Prime Minister he visited Michael Faraday's laboratory and asked if some esoteric substance called "Electricity" would ever have practical significance.

"One day, sir, you will tax it." was his answer.*

*Quoted in *Science,* 1994. As Michael Saunders points out, this cannot be correct because Faraday died in 1867 and Gladstone became prime minister in 1868. A more plausible prime minister would be Peel as electricity was discovered in 1831. Equally well it may be an urban legend.

6.1 ELECTRICITY: WHAT IS IT?

Water and wastewater operators generally have little difficulty in recognizing electrical equipment. Electrical equipment is everywhere and is easy to spot. For example, typical plant sites are outfitted with electrical equipment that

1. Generates electricity (a generator — or emergency generator)
2. Stores electricity (batteries)
3. Changes electricity from one form to another (transformers)
4. Transports or transmits and distributes electricity throughout the plant site (wiring distribution systems)
5. Measure electricity (meters)
6. Converts electricity into other forms of energy (rotating shafts — mechanical energy, heat energy, light energy, chemical energy, or radio energy)
7. Protects other electrical equipment (fuses, circuit breakers, or relays)
8. Operates and controls other electrical equipment (motor controllers)
9. Converts some condition or occurrence into an electric signal (sensors)
10. Converts some measured variable to a representative electrical signal (transducers or transmitters).

Recognizing electrical equipment is easy because we use so much of it. If we ask typical operators where such equipment is located in their plant site, they know, because they probably operate these devices or their ancillaries. If we asked these same operators what a particular electrical device does, they could probably tell us. If we were to ask if their plant electrical equipment was important to plant operations, the chorus would resound, "absolutely."

There is another question that does not always result in such a resounding note of assurance. If we asked these same operators to explain to us in very basic terms how electricity works to make their plant equipment operate, the answers we probably would receive would be varied, jumbled, disjointed, and probably not all that accurate. Even on a more basic level, how many operators would be able to accurately answer the question, what is electricity?

Probably very few operators would be able to answer this. Why do so many operators in both water and wastewater know so little about electricity? Part of the answer resides in the fact that operators are expected to know so much (and they are — and do), but are given so little opportunity to be properly trained.

We all know that experience is the great trainer. As an example, let us look at what an operator assigned to change the bearings on a 5-hp 3-phase motor would need to know to accomplish this task. (Note: Remember, it is not uncommon for water and wastewater operators to maintain as well as operate plant equipment.) The operator would have to know:

1. How to deenergize the equipment (i.e., proper lockout or tagout procedures)
2. Once deenergized, how to properly disassemble the motor coupling from the device it operates (e.g., a motor coupling from a pump shaft) and the proper tools to use
3. Once uncoupled, how to know how to properly disassemble the motor end-bells (preferably without damaging the rotor shaft)
4. Once disassembled, how to recognize if the bearings are really in need of replacement (though once removed from the end-bells, the bearings are typically replaced)

Questions the operator would need answered include the following:

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1. If the bearings are in need of replacement, how are they to be removed without causing damage to the rotor shaft?
2. Once removed, what bearings should be used to replace the old bearings?
3. When the proper bearings are identified and obtained, how are they to be installed properly?
4. When the bearings are replaced properly, how is the motor to be reassembled properly?
5. Once the motor is correctly put back together, how is it properly aligned to the pump and then reconnected?
6.. What is the test procedure to ensure that the motor has been restored properly to full operational status?

Every one of the steps and questions on the above procedures is important — errors at any point in the procedure could cause damage (maybe more damage than occurred in the first place). Another question is, does the operator really need to know electricity to perform the sequence of tasks described above?

The short answer is no, not exactly. Fully competent operators (who received most of their training via on-the-job experience) are usually qualified to perform the bearing-change-out activity on most plant motors with little difficulty.

The long answer is yes. Consider the motor mechanic who tunes your automobile engine. Then ask yourself, is it important that the auto mechanic have some understanding of internal combustion engines? We think it is important. You probably do, too. We also think it is important for the water or wastewater operator who changes bearings on an electrical motor to have some understanding of how the electric motor operates.

Here is another issue to look at. Have you ever taken an operator's state licensure examination? If you have, then you know that, typically, these examinations test the examinee's knowledge of basic electricity. (Note: This is especially the case for water operators.) Therefore, some states certainly consider operator knowledge of electricity important.

For reasons of licensure and of job competence, water/wastewater operators should have some basic electrical knowledge. How and where can operators quickly and easily learn this important information?

In this chapter, we provide the how and the where — here and now.

6.2 NATURE OF ELECTRICITY

The word electricity is derived from the Greek word electron (meaning amber). Amber is a translucent (semitransparent) yellowish fossilized mineral resin. The ancient Greeks used the words electric force in referring to the mysterious forces of attraction and repulsion exhibited by amber when it was rubbed with a cloth. They did not understand the nature of this force. They could not answer the question, "What is electricity?" The fact is this question still remains unanswered. Today, we often attempt to answer this question by describing the effect and not the force. That is, the standard answer given is, "the force that moves electrons" is electricity; this is about the same as defining a sail as "that force that moves a sailboat."

At the present time, little more is known than the ancient Greeks knew about the fundamental nature of electricity, but we have made tremendous strides in harnessing and using it. As with many other unknown (or unexplainable) phenomena, elaborate theories concerning the nature and behavior of electricity have been advanced and have gained wide acceptance because of their apparent truth — and because they work.

Scientists have determined that electricity seems to behave in a constant and predictable manner in given situations or when subjected to given conditions. Scientists, such as Michael Faraday, George Ohm, Frederick Lenz, and Gustav Kirchhoff, have described the predictable characteristics of electricity and electric current in the form of certain rules. These rules are often referred to as laws. Though electricity itself has never been clearly defined, its predictable nature and form of energy has made it one of the most widely used power sources in modern times.

The bottom line on what you need to learn about electricity can be summed up as follows: anyone can learn about electricity by learning the rules or laws applying to the behavior of electricity; and by understanding the methods of producing, controlling, and using it. Thus, this learning can be accomplished without ever having determined its fundamental identity.

You are probably scratching your head — puzzled.

I understand the main question running through the reader's brain cells at this exact moment: "This is a chapter about basic electricity and the author cannot even explain what electricity is?"

That is correct; we cannot. The point is no one can definitively define electricity. Electricity is one of those subject areas where the old saying, "we don't know what we don't know about it," fits perfectly.

Again, there are a few theories about electricity that have so far stood the test of extensive analysis and much time (relatively speaking, of course). One of the oldest and most generally accepted theories concerning electric current flow (or electricity), is known as the electron theory.

The electron theory states that electricity or current flow is the result of the flow of free electrons in a conductor. Thus, electricity is the flow of free electrons or simply electron flow. In addition, this is how we define electricity in this text —electricity is the flow of free electrons.

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Electrons are extremely tiny particles of matter. To gain understanding of electrons and exactly what is meant by electron flow, it is necessary to briefly discuss the structure of matter.

6.3 THE STRUCTURE OF MATTER

Matter is anything that has mass and occupies space. To study the fundamental structure or composition of any type of matter, it must be reduced to its fundamental components. All matter is made of molecules, or combinations of atoms (Greek: not able to be divided), that are bound together to produce a given substance, such as salt, glass, or water. For example, if we divide water into smaller and smaller drops, we would eventually arrive at the smallest particle that was still water. That particle is the molecule, which is defined as the smallest bit of a substance that retains the characteristics of that substance.

Note: Molecules are made up of atoms, which are bound together to produce a given substance.

Atoms are composed, in various combinations, of subatomic particles of electrons, protons, and neutrons. These particles differ in weight (a proton is much heavier than the electron) and charge. We are not concerned with the weights of particles in this text, but the charge is extremely important in electricity. The electron is the fundamental negative charge (–) of electricity. Electrons revolve about the nucleus or center of the atom in paths of concentric orbits, or shells (see Figure 6.1). The proton is the fundamental positive (+) charge of electricity. Protons are found in the nucleus. The number of protons within the nucleus of any particular atom specifies the atomic number of that atom. For example, the helium atom has 2 protons in its nucleus so the atomic number is 2. The neutron, which is the fundamental neutral charge of electricity, is also found in the nucleus.

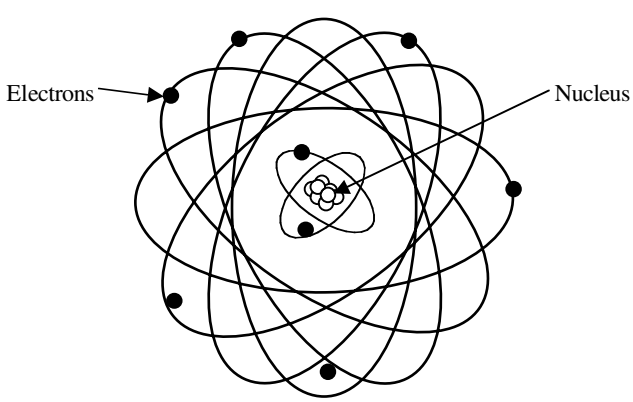

FIGURE 6.1 Electrons and nucleus of an atom. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

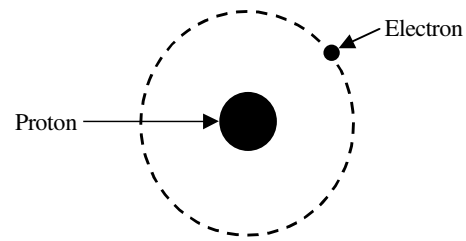

FIGURE 6.2 One proton and one electron = electrically neutral. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Most of the weight of the atom is in the protons and neutrons of the nucleus. Whirling around the nucleus is one or more negatively charged electrons. Normally, there is one proton for each electron in the entire atom, so that the net positive charge of the nucleus is balanced by the net negative charge of the electrons rotating around the nucleus (see Figure 6.2).

Note: Most batteries are marked with the symbols + and – or even with the abbreviations POS (positive) and NEG (negative). The concept of a positive or negative polarity and its importance in electricity will become clear later. However, for the moment, we need to remember that an electron has a negative charge and that a proton has a positive charge.

We stated earlier that in an atom the number of protons is usually the same as the number of electrons. This is an important point because this relationship determines the kind of element (the atom is the smallest particle that makes up an element; an element retains its characteristics when subdivided into atoms) in question. Figure 6.3 shows a simplified drawing of several atoms of different materials based on the conception of electrons orbiting about the nucleus. For example, hydrogen has a nucleus consisting of one proton, around which rotates one electron. The helium atom has a nucleus containing two protons and two neutrons, with two electrons encircling the nucleus. Both of these elements are electrically neutral (or balanced) because each has an equal number of electrons and protons. Since the negative (–) charge of each electron is equal in magnitude to the positive (+) charge of each proton, the two opposite charges cancel.

A balanced (neutral or stable) atom has a certain amount of energy that is equal to the sum of the energies of its electrons. Electrons, in turn, have different energies called energy levels. The energy level of an electron is proportional to its distance from the nucleus. Therefore, the energy levels of electrons in shells further from the nucleus are higher than that of electrons in shells nearer the nucleus.

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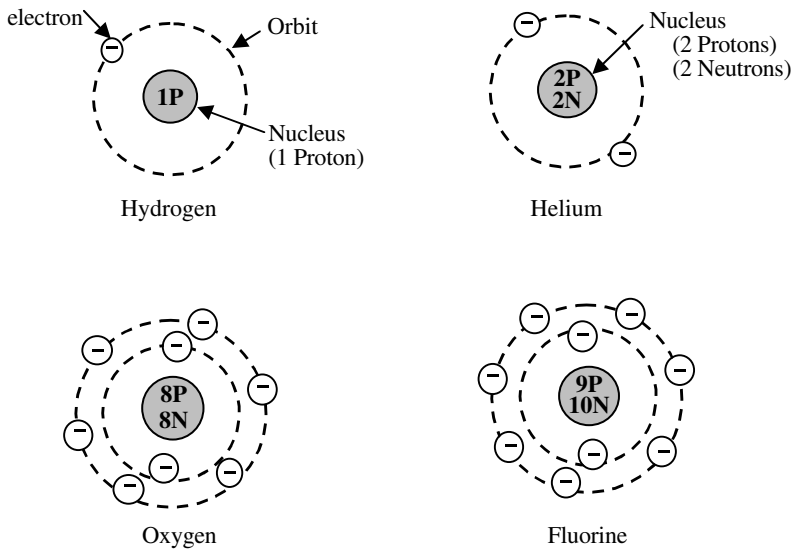

FIGURE 6.3 Atomic structure of elements. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

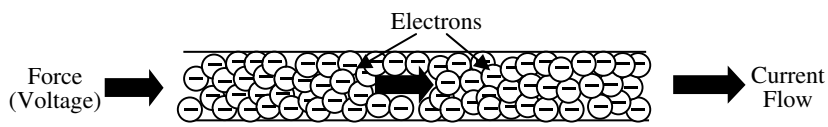

FIGURE 6.4 Electron flow in a copper wire. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

When an electric force is applied to a conducting medium, such as copper wire, electrons in the outer orbits of the copper atoms are forced out of orbit (i.e., liberating or freeing electrons) and are impelled along the wire. This electrical force, which forces electrons out of orbit, can be produced in a number of ways, such as by moving a conductor through a magnetic field; by friction, as when a glass rod is rubbed with cloth (silk); or by chemical action, as in a battery.

When the electrons are forced from their orbits, they are called free electrons. Some of the electrons of certain metallic atoms are so loosely bound to the nucleus that they are relatively free to move from atom to atom. These free electrons constitute the flow of an electric current in electrical conductors.

Note: When an electric force is applied to a copper wire, free electrons are displaced from the copper atoms and move along the wire, producing electric current as shown in Figure 6.4.

If the internal energy of an atom is raised above its normal state, the atom is said to be excited. Excitation may be produced by causing the atoms to collide with particles that are impelled by an electric force as shown in Figure 6.4. In effect, what occurs is that energy is transferred from the electric source to the atom. The excess energy absorbed by an atom may become sufficient to cause loosely bound outer electrons (as shown in Figure 6.4) to leave the atom against the force that acts to hold them within.

Note: An atom that has lost or gained one or more electrons is said to be ionized. If the atom loses electrons it becomes positively charged and is referred to as a positive ion. Conversely, if the atom gains electrons, it becomes negatively charged and is referred to as a negative ion.

6.4 CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

Electric current moves easily through some materials, but with greater difficulty through others. Substances that permit the free movement of a large number of electrons are called conductors. The most widely used electrical conductor is copper because of its high conductivity (how good a conductor the material is) and cost-effectiveness.

Electrical energy is transferred through a copper or other metal conductor by means of the movement of free electrons that migrate from atom to atom inside the conductor (see Figure 6.4). Each electron moves a very short distance to the neighboring atom where it replaces one or

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TABLE 6.1
Electrical Conductors

Silver	Brass
Copper	Iron
Gold	Tin
Aluminum	Mercury
Zinc	

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

TABLE 6.2
Common Insulators

Rubber	Plastics
Mica	Glass
Wax or paraffin	Fiberglass
Porcelain	Dry wood
Bakelite	Air

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

more electrons by forcing them out of their orbits. The replaced electrons repeat the process in other nearby atoms until the movement is transmitted throughout the entire length of the conductor. A good conductor is said to have a low opposition, or resistance, to the electron (current) flow.

Note: If lots of electrons flow through a material with only a small force (voltage) applied, we call that material a conductor.

Table 6.1 lists many of the metals commonly used as electric conductors. The best conductors appear at the top of the list, with the poorer ones shown last.

Note: The movement of each electron (e.g., in copper wire) takes a very small amount of time, almost instantly. This is an important point to keep in mind later in the book, when events in an electrical circuit seem to occur simultaneously.

While it is true that electron motion is known to exist to some extent in all matter, some substances, such as rubber, glass, and dry wood have very few free electrons. In these materials, large amounts of energy must be expended in order to break the electrons loose from the influence of the nucleus. Substances containing very few free electrons are called insulators. Insulators are important in electrical work because they prevent the current from being diverted from the wires.

Note: If the voltage is large enough, even the best insulators will break down and allow their electrons to flow.

Table 6.2 lists some materials that we often use as insulators in electrical circuits. The list is in decreasing order of ability to withstand high voltages without conducting.

A material that is neither a good conductor nor a good insulator is called a semiconductor. Silicon and germanium are substances that fall into this category. Because of their peculiar crystalline structure, these materials may under certain conditions act as conductors; under other conditions they act as insulators. As the temperature is raised, however, a limited number of electrons become available for conduction.

6.5 STATIC ELECTRICITY

Electricity at rest is often referred to as static electricity. More specifically, when two bodies of matter have unequal charges, and are near one another, an electric force is exerted between them because of their unequal charges. Because they are not in contact, their charges cannot equalize. The existence of such an electric force where current cannot flow is static electricity.

Static, or electricity at rest, will flow if given the opportunity. An example of this phenomenon is often experienced when one walks across a dry carpet and then touches a doorknob; a slight shock is usually felt and a spark at the fingertips is likely noticed. In the workplace, static electricity is prevented from building up by properly bonding equipment to ground or earth.

6.5.1 Charged Bodies

To fully grasp the understanding of static electricity, it is necessary to know one of the fundamental laws of electricity and its significance.

The fundamental law of charged bodies states that like charges repel each other and unlike charges attract each other.

A positive charge and negative charge, being opposite or unlike, tend to move toward each other, attracting each other. In contrast, like bodies tend to repel each other. Electrons repel each other because of their like negative charges, and protons repel each other because of their like positive charges. Figure 6.5 demonstrates the law of charged bodies.

It is important to point out another significant part of the fundamental law of charged bodies — the force of attraction or repulsion existing between two magnetic poles decreases rapidly as the poles are separated from each other. More specifically, the force of attraction or repulsion varies directly as the product of the separate pole strengths and inversely as the square of the distance

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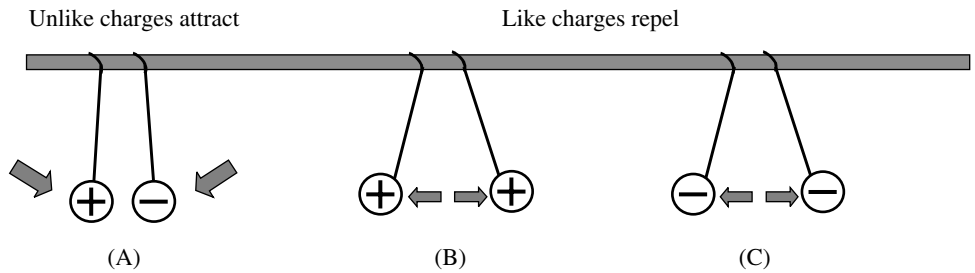

FIGURE 6.5 Reaction between two charged bodies. The opposite charge in (A) attracts. The like charges in (B) and (C) repel each other. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

separating the magnetic poles, provided the poles are small enough to be considered as points.

Let us look at an example. If we increased the distance between 2 north poles from 2 to 4 ft, the force of repulsion between them is decreased to 1/4 of its original value. If either pole strength is doubled, the distance remaining the same, the force between the poles will be doubled.

6.5.2 Coulomb's Law

Simply put, Coulomb's law points out that the amount of attracting or repelling force that acts between two electrically charged bodies in free space depends on two things:

1. Their charges
2. The distance between them

Specifically, Coulomb's law states, "Charged bodies attract or repel each other with a force that is directly proportional to the product of their charges, and is inversely proportional to the square of the distance between them."

Note: The magnitude of electric charge a body possesses is determined by the number of electrons compared with the number of protons within the body. The symbol for the magnitude of electric charge is Q, expressed in units of coulombs (C). A charge of + 1 C means a body contains a charge of 6.25×10^{18}. A charge of –1 C means a body contains a charge of 6.25×10^{18} more electrons than protons.

6.5.3 Electrostatic Fields

The fundamental characteristic of an electric charge is its ability to exert force. The space between and around charged bodies in which their influence is felt is called an electric field of force. The electric field is always terminated on material objects and extends between positive and negative charges. This region of force can consist of air, glass, paper, or a vacuum, and is referred to as an electrostatic field.

When two objects of opposite polarity are brought near each other, the electrostatic field is concentrated in the area between them. Lines that are referred to as electrostatic lines of force generally represent the field. These lines are imaginary and are used merely to represent the direction and strength of the field. To avoid confusion, the positive lines of force are always shown leaving charge, and for a negative charge, they are shown as entering. Figure 6.6 illustrates the use of lines to represent the field about charged bodies.

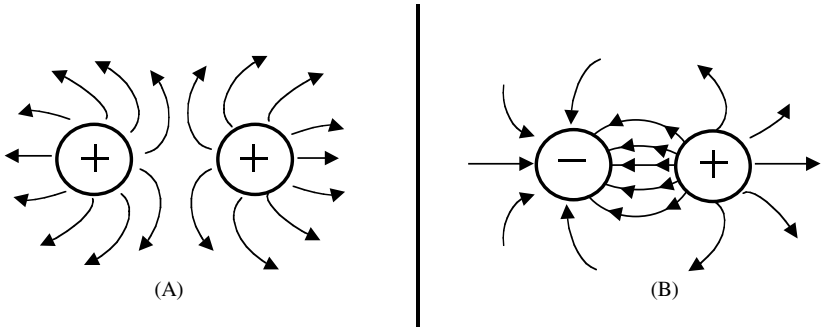

FIGURE 6.6 Electrostatic lines of force: (A) represents the repulsion of like-charged bodies and their associated fields; (B) represents the attraction between unlike-charged bodies and their associated fields. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Note: A charged object will retain its charge temporarily if there is no immediate transfer of electrons to or from it. In this condition, the charge is said to be at rest. Remember, electricity at rest is called static electricity.

6.6 MAGNETISM

Most electrical equipment depends directly or indirectly upon magnetism. Magnetism is defined as a phenomena associated with magnetic fields; it has the power to attract such substances as iron, steel, nickel, or cobalt (metals that are known as magnetic materials). Correspondingly, a substance is said to be a magnet if it has the property of magnetism. For example, a piece of iron can be magnetized and therefore is a magnet.

When magnetized, the piece of iron (note: we will assume a piece of flat bar is $6 \times 1 \times 5$ in.; a bar magnet — see Figure 6.7) will have two points opposite each other, which most readily attract other pieces of iron. The points of maximum attraction (one on each end) are called the *magnetic* poles of the magnet: the north (N) pole and the south (S) pole. Just as like electric charges repel each other and opposite charges attract each other, like magnetic poles repel each other and unlike poles attract each other. Although invisible to the naked eye, its force can be shown to exist by sprinkling small iron filings on a glass covering a bar magnet as shown in Figure 6.7.

Figure 6.8 shows how the field looks without iron filings; it is shown as lines of force (known as **magnetic flux** or flux lines; the symbol for magnetic flux is the Greek lowercase letter ϕ [phi]) in the field, repelled away from the north pole of the magnet and attracted to its south pole.

Note: A magnetic circuit is a complete path through which magnetic lines of force may be established under the influence of a magnetizing force. Most magnetic circuits are composed largely of magnetic materials in order to contain the magnetic flux. These circuits are similar to the electric circuit (an important point), which is a complete path through which current is caused to flow under the influence of an electromotive force.

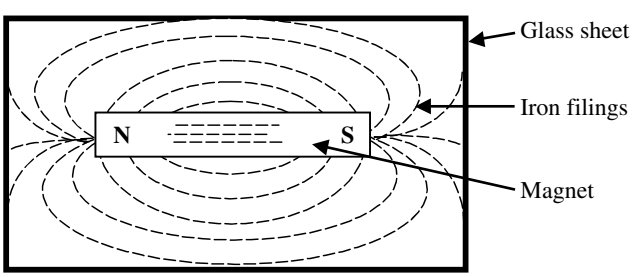

FIGURE 6.7 Shows the magnetic field around a bar magnet. If the glass sheet is tapped gently, the filings will move into a definite pattern that describes the field of force around the magnet. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

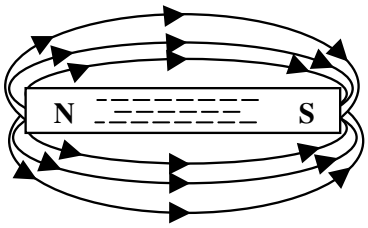

FIGURE 6.8 Magnetic field of force around a bar magnet, indicated by lines of force. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

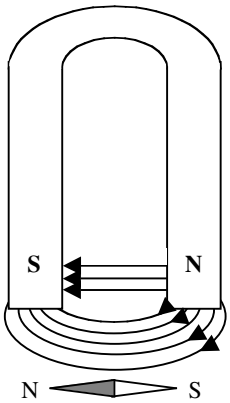

FIGURE 6.9 Horseshoe magnet. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

There are three types or groups of magnets:

1. Natural magnets — These magnets are found in the natural state in the form of a mineral (an iron compound) called magnetite.
2. Permanent magnets (artificial magnet) — These magnets are hardened steel or some alloy, such as Alnico bars, that has been permanently magnetized. The permanent magnet most people are familiar with is the horseshoe magnet (see Figure 6.9).
3. Electromagnets (artificial magnet) — These magnets are composed of soft-iron cores around which are wound coils of insulated wire. When an electric current flows through the coil, the core becomes magnetized. When the current ceases to flow, the core loses most of the magnetism.

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6.6.1 Magnetic Materials

Natural magnets are no longer used (they have no practical value) in electrical circuitry because more powerful and more conveniently shaped permanent magnets can be produced artificially. Commercial magnets are made from special steels and alloys — magnetic materials.

Magnetic materials are those materials that are attracted or repelled by a magnet and that can be magnetized. Iron, steel, and alloy bar are the most common magnetic materials. These materials can be magnetized by inserting the material (in bar form) into a coil of insulated wire and passing a heavy direct current through the coil. The same material may also be magnetized if it is stroked with a bar magnet. It will then have the same magnetic property that the magnet used to induce the magnetism has; there will be two poles of attraction, one at either end. This process produces a permanent magnet by induction —the magnetism is induced in the bar by the influence of the stroking magnet.

Note: Permanent magnets are those of hard magnetic materials (hard steel or alloys) that retain their magnetism when the magnetizing field is removed. A temporary magnet is one that has no ability to retain a magnetized state when the magnetizing field is removed.

Even though classified as permanent magnets, it is important to point out that hardened steel and certain alloys are relatively difficult to magnetize and are said to have a low permeability. This is because the magnetic lines of force do not easily permeate, or distribute themselves, readily through the steel.

Note: Permeability refers to the ability of a magnetic material to concentrate magnetic flux. Any material that is easily magnetized has high permeability. A measure of permeability for different materials in comparison with air or vacuum is called relative permeability, symbolized by μ or (mu).

Once hard steel and other alloys are magnetized, they retain a large part of their magnetic strength and are called permanent magnets. Conversely, materials that are relatively easy to magnetize, such as soft iron and annealed silicon steel, are said to have a high permeability. Such materials retain only a small part of their magnetism after the magnetizing force is removed and are called temporary magnets.

The magnetism that remains in a temporary magnet after the magnetizing force is removed is called residual magnetism.

Early magnetic studies classified magnetic materials merely as being magnetic and nonmagnetic, meaning based on the strong magnetic properties of iron. However, because weak magnetic materials can be important in some applications, present studies classify materials into one of three groups: paramagnetic, diamagnetic, and ferromagnetic.

1. Paramagnetic materials — These include aluminum, platinum, manganese, and chromium — materials that become only slightly magnetized even though they are under the influence of a strong magnetic field. This slight magnetization is in the same direction as the magnetizing field. Relative permeability is slightly more than 1 (i.e., considered nonmagnetic materials).
2. Diamagnetic materials — These include bismuth, antimony, copper, zinc, mercury, gold, and silver — materials that can also be slightly magnetized when under the influence of a very strong field. Relative permeability is less than 1 (i.e., considered nonmagnetic materials).
3. Ferromagnetic materials — These include iron, steel, nickel, cobalt, and commercial alloys — materials that are the most important group for applications of electricity and electronics. Ferromagnetic materials are easy to magnetize and have high permeability, ranging from 50 to 3000.

6.6.2 Magnetic Earth

The earth is a huge magnet, and surrounding earth is the magnetic field produced by the earth's magnetism. Most people would have no problem understanding or at least accepting this statement. If people were told that the earth's north magnetic pole is actually its south magnetic pole and that the south magnetic pole is actually the earth's north magnetic pole, they might not accept or understand this statement. However, in terms of a magnet, it is true.

As can be seen from Figure 6.10, the magnetic polarities of the earth are indicated. The geographic poles are also shown at each end of the axis of rotation of the earth. Clearly, as shown in Figure 6.10, the magnetic axis does not coincide with the geographic axis. Therefore, the magnetic and geographic poles are not at the same place on the surface of the earth.

Recall that magnetic lines of force are assumed to emanate from the north pole of a magnet and to enter the south pole as closed loops. Because the earth is a magnet, lines of force emanate from its north magnetic pole and enter the south magnetic pole as closed loops. A compass needle aligns itself in such a way that the earth's lines of force enter at its south pole and leave at its north pole. Because the north pole of the needle is defined as the end that points in a northerly direction, it follows that the magnetic pole near the north geographic pole is in reality a south magnetic pole and vice versa.

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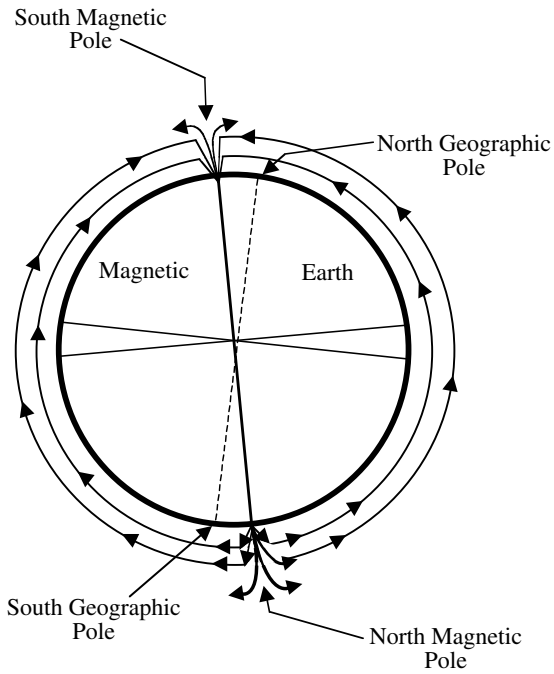

FIGURE 6.10 Earth's magnetic poles. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.7 DIFFERENCE IN POTENTIAL

Because of the force of its electrostatic field, an electric charge has the ability to do the work of moving another charge by attraction or repulsion. The force that causes free electrons to move in a conductor as an electric current may be referred to as follows:

1. Electromotive force (EMF)
2. Voltage
3. Difference in potential

When a difference in potential exists between two charged bodies that are connected by a wire (conductor), electrons (current) will flow along the conductor. This flow is from the negatively charged body to the positively charged body until the two charges are equalized and the potential difference no longer exists.

Note: The basic unit of potential difference is the volt (V). The symbol for potential difference is V, indicating the ability to do the work of forcing electrons (current flow) to move. Because the volt unit is used, potential difference is called voltage.

6.7.1 The Water Analogy

In attempting to train individuals in the concepts of basic electricity, especially in regards to difference of potential (voltage), current, and resistance relationships in a simple electrical circuit, it has been common practice to use what is referred to as the water analogy. We use the water analogy later to explain (in a simple, straightforward fashion) voltage, current, and resistance and their relationships in more detail. For now we use the analogy to explain the basic concept of electricity: difference of potential, or voltage. Because a difference in potential causes current flow (against resistance), it is important that this concept be understood first before the concept of current flow and resistance are explained.

Consider the water tanks shown in Figure 6.11 — two water tanks connected by a pipe and valve. At first, the valve is closed and all the water is in Tank A. Thus, the water pressure across the valve is at its maximum. When the valve is opened, the water flows through the pipe from A to B until the water level becomes the same in both tanks. The water then stops flowing in the pipe, because there is no longer a difference in water pressure (difference in potential) between the two tanks.

Just as the flow of water through the pipe in Figure 6.11 is directly proportional to the difference in water level in the two tanks, current flow through an electric circuit is directly proportional to the difference in potential across the circuit.

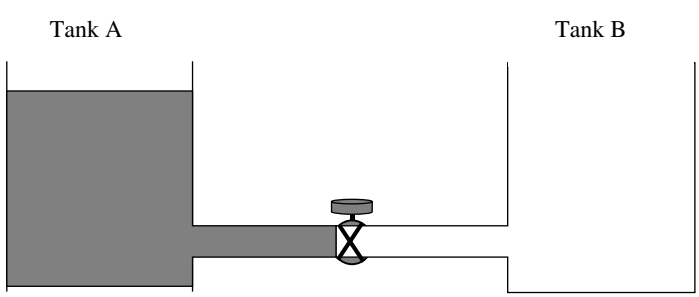

FIGURE 6.11 Water analogy of electric difference of potential. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Important Point: A fundamental law of current electricity is that the current is directly proportional to the applied voltage; that is, if the voltage is increased, the current is increased. If the voltage is decreased, the current is decreased.

6.7.2 Principal Methods of Producing Voltage

There are many ways to produce electromotive force, or voltage. Some of these methods are much more widely used than others. The following is a list of the six most common methods of producing electromotive force.

1. Friction — Voltage produced by rubbing two materials together.
2. Pressure (piezoelectricity) — Voltage produced by squeezing crystals of certain substances.
3. Heat (thermoelectricity) — Voltage produced by heating the joint (junction) where two unlike metals are joined.
4. Light (photoelectricity) — Voltage produced by light striking photosensitive (light sensitive) substances.
5. Chemical action — Voltage produced by chemical reaction in a battery cell.
6. Magnetism — Voltage produced in a conductor when the conductor moves through a magnetic field, or a magnetic field moves through the conductor in such a manner as to cut the magnetic lines of force of the field.

In the study of basic electricity, we are most concerned with magnetism and chemistry as a means to produce voltage. Friction has little practical applications, though we discussed it earlier in static electricity. Pressure, heat, and light do have useful applications, but we do not need to consider them in this text. Magnetism and chemistry, on the other hand, are the principal sources of voltage and are discussed at length in this text.

6.8 CURRENT

The movement or the flow of electrons is called *current*. To produce current, the electrons must be moved by a potential difference.

Note: The terms current, current flow, electron flow, or electron current, etc., may be used to describe the same phenomenon.

Electron flow, or current, in an electric circuit is from a region of less negative potential to a region of more positive potential.

Note: The letter I is the basic unit that represents current measured in amperes or amps (A). The measurement of 1 A of current is defined as the movement of 1 C past any point of a conductor during 1 sec of time.

Earlier we used the water analogy to help us understand potential difference. We can also use the water analogy to help us understand current flow through a simple electric circuit.

Figure 6.12 shows a water tank connected via a pipe to a pump with a discharge pipe. If the water tank contains an amount of water above the level of the pipe opening to the pump, the water exerts pressure (a difference in potential) against the pump. When sufficient water is available for pumping with the pump, water flows through the pipe against the resistance of the pump and pipe. The analogy should be clear — in an electric circuit, if a difference of potential exists, current will flow in the circuit.

Another simple way of looking at this analogy is to consider Figure 6.13 where the water tank has been replaced with a generator, the pipe with a conductor (wire), and water flow with the flow of electric current.

Again, the key point illustrated by Figure 6.12 and Figure 6.13 is that to produce current, the electrons must be moved by a potential difference.

Electric current is generally classified into two general types:

1. Direct current (DC)
2. Alternating current (AC)

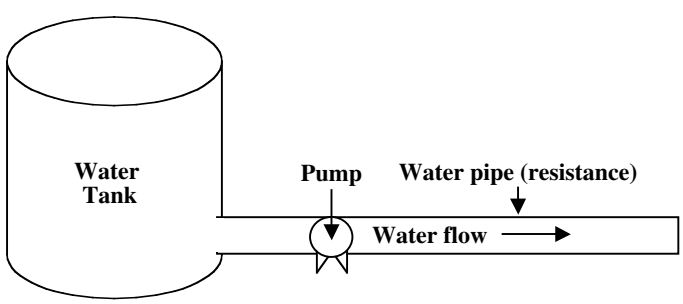

FIGURE 6.12 Water analogy: current flow. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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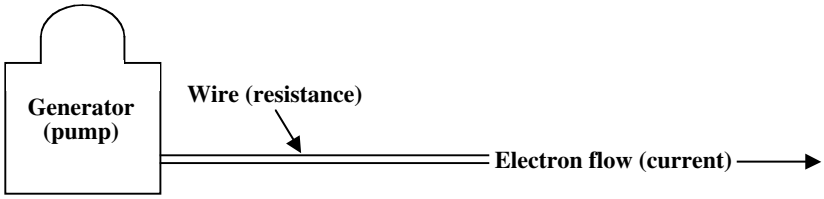

FIGURE 6.13 Simple electric circuit with current flow. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Direct current is current that moves through a conductor or circuit in one direction only. Alternating current periodically reverses direction.

6.9 RESISTANCE

In Section 6.4, we discussed conductors and insulators. We pointed out that free electrons, or electric current, could move easily through a good conductor, such as copper, but that an insulator, such as glass, was an obstacle to current flow. In the water analogy shown in Figure 6.12 and the simple electric circuit shown in Figure 6.13, either the pipe or the conductor indicates resistance.

Every material offers some resistance, or opposition, to the flow of electric current through it. Good conductors, such as copper, silver, and aluminum, offer very little resistance. Poor conductors, or insulators, such as glass, wood, and paper, offer a high resistance to current flow.

Note: The amount of current that flows in a given circuit depend on two factors: voltage and resistance.

Note: The letter R represents resistance. The basic unit in which resistance is measured is the ohm (Ω). The measurement of 1 Ω is the resistance of a circuit element, or circuit, that permits a steady current of 1 ampere (1 C/sec) to flow when a steady EMF of 1 V is applied to the circuit. Manufactured circuit parts containing definite amounts of resistance are called resistors.

The size and type of material of the wires in an electric circuit are chosen to keep the electrical resistance as low as possible. In this way, current can flow easily through the conductors, just as water flows through the pipe between the tanks in Figure 6.11. If the water pressure remains constant, the flow of water in the pipe will depend on how far the valve is opened. The smaller the opening, the greater the opposition (resistance) to the flow, and the smaller the rate of flow will be in gallons per second.

In the simple electric circuit shown in Figure 6.13, the larger the diameter of the wire, the lower will be its electrical resistance (opposition) to the flow of current through it. In the water analogy, pipe friction opposes the flow of water between the tanks. This friction is similar to electrical resistance. The resistance of the pipe to the flow of water through it depends upon

1. The length of the pipe
2. Diameter of the pipe
3. The nature of the inside walls (rough or smooth)

Similarly, the electrical resistance of the conductors depends upon

1. The length of the wires
2. The diameter of the wires
3. The material of the wires (copper, silver, etc.)

It is important to note that temperature also affects the resistance of electrical conductors to some extent. In most conductors (copper, aluminum, etc.) the resistance increases with temperature. Carbon is an exception. In carbon, the resistance decreases as temperature increases.

Important Note: Electricity is a study that is frequently explained in terms of opposites. The term that is exactly the opposite of resistance is conductance. Conductance (G) is the ability of a material to pass electrons. The unit of conductance is the Mho, which is ohm spelled backwards. The relationship that exists between resistance and conductance is the reciprocal. A reciprocal of a number is obtained by dividing the number into one. If the resistance of a material is known, dividing its value into one will give its conductance. Similarly, if the conductance is known, dividing its value into one will give its resistance.

6.10 BATTERY-SUPPLIED ELECTRICITY

Battery-supplied direct current electricity has many applications and is widely used in water and wastewater treatment operations. Applications include providing electrical energy in plant vehicles and emergency diesel generators; material handling equipment (forklifts); portable electric or electronic equipment; backup emergency power for light-packs, hazard warning signal lights, and flashlights;

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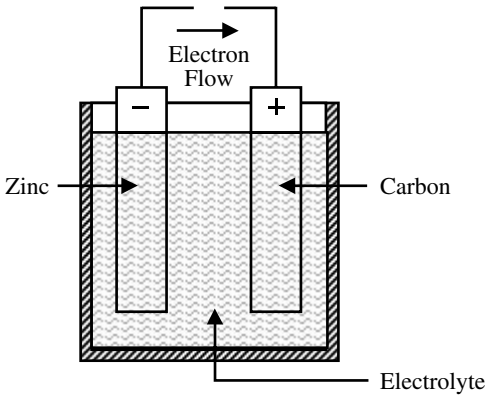

FIGURE 6.14 Simple voltaic cell. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

and standby power supplies or uninterruptible power supplies for computer systems. In some instances, they are used as the only source of power, while in others (as mentioned above) they are used as a secondary or standby power supply.

6.10.1 The Voltaic Cell

The simplest cell (a device that transforms chemical energy into electrical energy) is known as a *voltaic* (or galvanic) cell (see Figure 6.14). It consists of a piece of carbon (C) and a piece of zinc (Zn) suspended in a jar that contains a solution of water (H_2O) and sulfuric acid (H_2SO_4).

Note: A simple cell consists of two strips, or electrodes, placed in a container that hold the electrolyte. A battery is formed when two or more cells are connected.

The electrodes are the conductors by which the current leaves or returns to the electrolyte. In the simple cell described above, they are carbon and zinc strips placed in the electrolyte. Zinc contains an abundance of negatively charged atoms, while carbon has an abundance of positively charge atoms. When the plates of these materials are immersed in an electrolyte, chemical action between the two begins.

In the dry cell (see Figure 6.15), the electrodes are the carbon rod in the center and the zinc container in which the cell is assembled.

The electrolyte is the solution that acts upon the electrodes that are placed in it. The electrolyte may be a salt, an acid, or an alkaline solution. In the simple voltaic cell and in the automobile storage battery, the electrolyte is in a liquid form, while in the dry cell (see Figure 6.15) the electrolyte is a moist paste.

6.10.2 Primary and Secondary Cells

Primary cells are normally those that cannot be recharged or returned to good condition after their voltage drops too low. Dry cells in flashlights and transistor radios are examples of primary cells. Some primary cells have been developed to the state where they can be recharged.

A secondary cell is one in which the electrodes and the electrolyte are altered by the chemical action that takes place when the cell delivers current. These cells are rechargeable. During recharging, the chemicals that provide electric energy are restored to their original condition. Recharging is accomplished by forcing an electric current through them in the opposite direction to that of discharge.

Connecting as shown in Figure 6.16 recharges a cell. Some battery chargers have a voltmeter and an ammeter that indicate the charging voltage and current.

The automobile storage battery is the most common example of the secondary cell.

6.10.3 Battery

As was stated previously, a battery consists of two or more cells placed in a common container. The cells are connected in series, in parallel, or in some combination of series and parallel, depending upon the amount of voltage and current required of the battery.

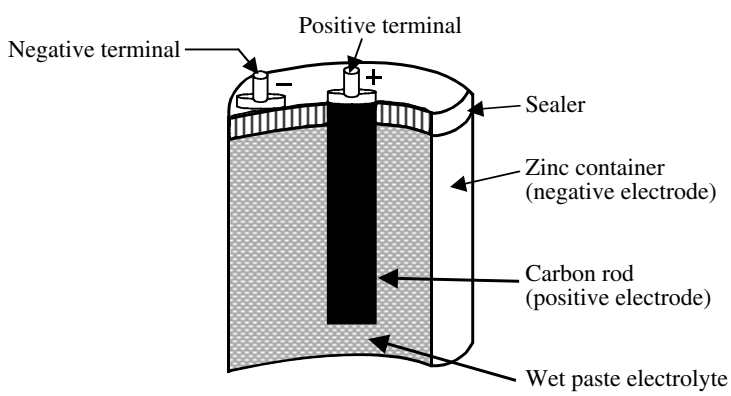

FIGURE 6.15 Dry cell (cross-sectional view). (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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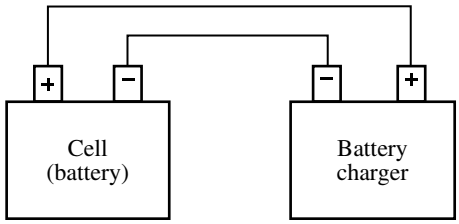

FIGURE 6.16 Hookup for charging a secondary cell with a battery charger. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.10.3.1 Battery Operation

The chemical reaction within a battery provides the voltage. This occurs when a conductor is connected externally to the electrodes of a cell, causing electrons to flow under the influence of a difference in potential across the electrodes from the zinc (negative) through the external conductor to the carbon (positive), returning within the solution to the zinc. After a short period, the zinc will begin to waste away because of the acid.

The voltage across the electrodes depends upon the materials from which the electrodes are made and the composition of the solution. The difference of potential between the carbon and zinc electrodes in a dilute solution of sulfuric acid and water is about 1.5 V.

The current that a primary cell may deliver depends upon the resistance of the entire circuit, including that of the cell. The internal resistance of the primary cell depends upon the size of the electrodes, the distance between them in the solution, and the resistance of the solution. The larger the electrodes and the closer together they are in solution (without touching), the lower the internal resistance of the primary cell and the more current it is capable of supplying to the load.

Note: When current flows through a cell, the zinc gradually dissolves in the solution and the acid is neutralized.

6.10.3.2 Combining Cells

In many operations, battery-powered devices may require more electrical energy than one cell can provide. Various devices may require either a higher voltage or more current, and some cases both. Under such conditions, it is necessary to combine, or interconnect, a sufficient number of cells to meet the higher requirements. Cells connected in series provide a higher voltage, while cells connected in parallel provide a higher current capacity. To provide adequate power when both voltage and current requirements are greater than the capacity of one cell, a combination series-parallel network of cells must be interconnected.

When cells are connected in series (see Figure 6.17), the total voltage across the battery of cells is equal to the sum of the voltage of each of the individual cells. In Figure 6.17, the 4 1.5-V cells in series provide a total battery voltage of 6 V. When cells are placed in series, the positive terminal of one cell is connected to the negative terminal of the other cell. The positive electrode of the first cell and negative electrode of the last cell then serve as the power takeoff terminals of the battery. The current flowing through such a battery of series cells is the same as from one cell because the same current flows through all the series cells.

To obtain a greater current, a battery has cells connected in parallel as shown in Figure 6.18. In this parallel connection, all the positive electrodes are connected to one line, and all negative electrodes are connected to the other. Any point on the positive side can serve as the positive terminal of the battery, and any point on the negative side can be the negative terminal.

The total voltage output of a battery of three parallel cells is the same as that for a single cell (Figure 6.18), but the available current is three times that of one cell; that is, the current capacity has been increased.

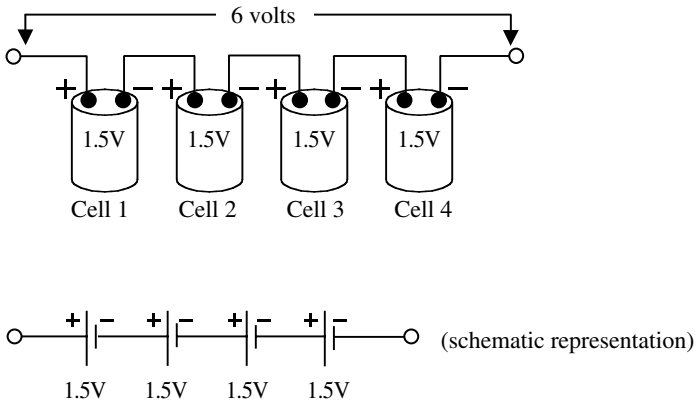

FIGURE 6.17 Cells in series. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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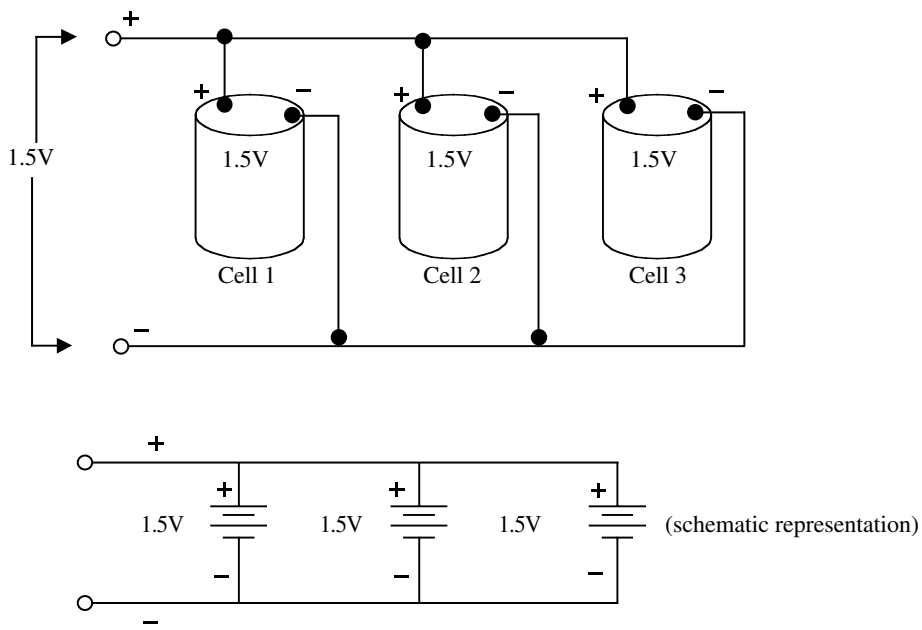

FIGURE 6.18 Cells in parallel. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

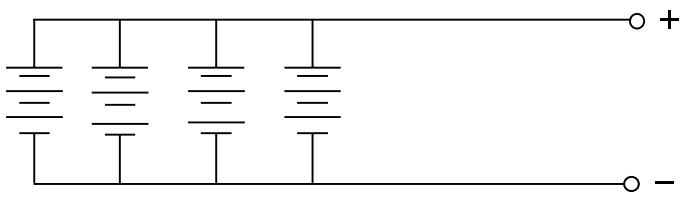

FIGURE 6.19 Series-parallel connected cells. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Identical cells in parallel all supply equal parts of the current to the load. For example, of 3 different parallel cells producing a load current of 210 mA, each cell contributes 70 mA.

Figure 6.19 depicts a schematic of a series-parallel battery network supplying power to a load requiring both a voltage and current greater than one cell can provide. To provide the required increased voltage, groups of three 1.5-V cells are connected in series. To provide the required increased amperage, four series groups are connected in parallel.

6.10.4 Types of Batteries

In the past 25 years, several different types of batteries have been developed. In this text, we briefly discuss five types: the dry cell, lead-acid battery, alkaline cell, nickel-cadmium, and mercury cell.

6.10.4.1 Dry Cell

The dry cell, or carbon-zinc cell, is so known because its electrolyte is not in a liquid state (however, the electrolyte is a moist paste). The dry cell battery is one of the oldest and most widely used commercial types of dry cell. The carbon, in the form of a rod that is placed in the center of the cell, is the positive terminal. The case of the cell is made of zinc, which is the negative terminal (see Figure 6.15). Between the carbon electrode and the zinc case is the electrolyte of a moist chemical paste-like mixture. The cell is sealed to prevent the liquid in the paste from evaporating. The voltage of a cell of this type is about 1.5 V.

6.10.4.2 Lead-Acid Battery

The lead-acid battery is a secondary cell, commonly termed a storage battery, that stores chemical energy until it is released as electrical energy.

Note: The lead-acid battery differs from the primary cell type battery mainly in that it may be recharged, whereas most primary cells are not normally recharged. In addition, the term storage battery is somewhat deceiving because this battery does not store electrical energy, but is a

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source of chemical energy that produces electrical energy.

As the name implies, the lead-acid battery consists of a number of lead-acid cells immersed in a dilute solution of sulfuric acid. Each cell has two groups of lead plates; one set is the positive terminal and the other is the negative terminal. Active materials within the battery (lead plates and sulfuric acid electrolyte) react chemically to produce a flow of direct current whenever current consuming devices are connected to the battery terminal posts. This current is produced by the chemical reaction between the active material of the plates (electrodes) and the electrolyte (sulfuric acid).

This type of cell produces slightly more than 2 V. Most automobile batteries contain 6 cells connected in series so that the output voltage from the battery is slightly more than 12 V.

Besides being rechargeable, the main advantage of the lead-acid storage battery over the dry cell battery is that the storage battery can supply current for a much longer time than the average dry cell.

Safety Note: Whenever a lead-acid storage battery is charging, the chemical action produces dangerous hydrogen gas; thus, the charging operation should only take place in a well-ventilated area.

6.10.4.3 Alkaline Cell

The alkaline cell is a secondary cell that gets its name from its alkaline electrolyte — potassium hydroxide. Another type battery, sometimes called the alkaline battery, has a negative electrode of zinc and a positive electrode of manganese dioxide. It generates 1.5 V.

6.10.4.4 Nickel-Cadmium Cell

The nickel-cadmium cell, or Ni-Cad cell, is the only dry battery that is a true storage battery with a reversible chemical reaction, allowing recharging many times. In the secondary nickel-cadmium dry cell, the electrolyte is potassium hydroxide, the negative electrode is nickel hydroxide, and the positive electrode is cadmium oxide. The operating voltage is 1.25 V. Because of its rugged characteristics (stands up well to shock, vibration, and temperature changes) and availability in a variety of shapes and sizes, it is ideally suited for use in powering portable communication equipment.

6.10.4.5 Mercury Cell

The mercury cell was developed because of space exploration activities — the development of small transceivers and miniaturized equipment where a power source of miniaturized size was needed. In addition to reduced size, the mercury cell has a good shelf life and is very rugged. Mercury cells also produce a constant output voltage under different load conditions.

There are two different types of mercury cells. One is a flat cell that is shaped like a button, while the other is a cylindrical cell that looks like a standard flashlight cell. The advantage of the button-type cell is that several of them can be stacked inside one container to form a battery. A cell produces 1.35 V.

6.10.4.6 Battery Characteristics

Batteries are generally classified by their various characteristics. Parameters such as internal resistance, specific gravity, capacity, and shelf life are used to classify batteries by type.

Regarding internal resistance, it is important to keep in mind that a battery is a DC voltage generator. As such, the battery has internal resistance. In a chemical cell, the resistance of the electrolyte between the electrodes is responsible for most of the cell's internal resistance. Because any current in the battery must flow through the internal resistance, this resistance is in series with the generated voltage. With no current, the voltage drop across the resistance is zero so that the full-generated voltage develops across the output terminals. This is the open-circuit voltage, or no-load voltage. If a load resistance is connected across the battery, the load resistance is in series with internal resistance. When current flows in this circuit, the internal voltage drop decreases the terminal voltage of the battery.

The ratio of the weight of a certain volume of liquid to the weight of the same volume of water is called the specific gravity of the liquid. Pure sulfuric acid has a specific gravity of 1.835 since it weighs 1.835 times as much as water per unit volume. The specific gravity of a mixture of sulfuric acid and water varies with the strength of the solution from 1.000 to 1.830.

The specific gravity of the electrolyte solution in a lead-acid cell ranges from 1.210 to 1.300 for new, fully charged batteries. The higher the specific gravity, the less internal resistance of the cell and the higher the possible load current. As the cell discharges, the water formed dilutes the acid and the specific gravity gradually decreases to about 1.150, at which time the cell is considered to be fully discharged.

The specific gravity of the electrolyte is measured with a **hydrometer**, which has a compressible rubber bulb at the top, a glass barrel, and a rubber hose at the bottom of the barrel. In taking readings with a hydrometer, the decimal point is usually omitted. For example, a specific gravity of 1.260 is read simply as "twelve-sixty." A hydrometer reading of 1210 to 1300 indicates full charge, about 1250 is half-charge, and 1150 to 1200 is complete discharge.

The capacity of a battery is measured in ampere-hours (Ah).

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Note: The ampere-hour capacity is equal to the product of the current in amperes and the time in hours during which the battery is supplying this current. The ampere-hour capacity varies inversely with the discharge current. The size of a cell is determined generally by its ampere-hour capacity.

The capacity of a storage battery determines how long it will operate at a given discharge rate and depends upon many factors. The most important of these are as follows:

1. The area of the plates in contact with the electrolyte
2. The quantity and specific gravity of the electrolyte
3. The type of separators
4. The general condition of the battery (degree of sulfating, plates bucked, separators warped, sediment in bottom of cells, etc.)
5. The final limiting voltage

The shelf life of a cell is that period of time during which the cell can be stored without losing more than approximately 10% of its original capacity. The loss of capacity of a stored cell is due primarily to the drying out of its electrolyte in a wet cell and to chemical actions that change the materials within the cell. Keeping it in a cool, dry place can extend the shelf life.

6.11 THE SIMPLE ELECTRICAL CIRCUIT

An electric circuit includes an energy source (source of EMF or voltage [a battery or generator]), a conductor (wire), a load, and a means of control (see Figure 6.20). The energy source could be a battery, as in Figure 6.20, or some other means of producing a voltage. The load that dissipates the energy could be a lamp, a resistor, or some other device (or devices) that does useful work, such as an electric toaster, a power drill, radio, or a soldering iron. Conductors are wires that offer low resistance to current; they connect all the loads in the circuit to the voltage source. No electrical device dissipates energy unless current flows through it. Because conductors, or wires, are not perfect conductors, they heat up (dissipate energy), so they are actually part of the load. For simplicity we usually think of the connecting wiring as having no resistance, since it would be tedious to assign a very low resistance value to the wires every time we wanted to solve a problem. Control devices might be switches, variable resistors, circuit breakers, fuses, or relays.

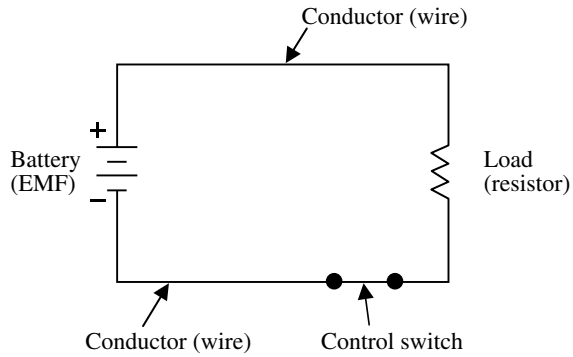

FIGURE 6.20 Simple closed circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

A complete pathway for current flow, or closed circuit (Figure 6.20), is an unbroken path for current from the EMF, through a load, and back to the source. A circuit is called open (see Figure 6.21) if a break in the circuit (e.g., open switch) does not provide a complete path for current.

Important Point: Current flows from the negative (–) terminal of the battery, shown in Figures 6.20 and 6.21, through the load to the positive (+) battery terminal, and continues by going through the battery from the positive (+) terminal to the negative (–) terminal. As long as this pathway is unbroken, it is a closed circuit and current will flow. However, if the path is broken at any point, it is an open circuit and no current flows.

To protect a circuit, a fuse is placed directly into the circuit (see Figure 6.22). A fuse will open the circuit

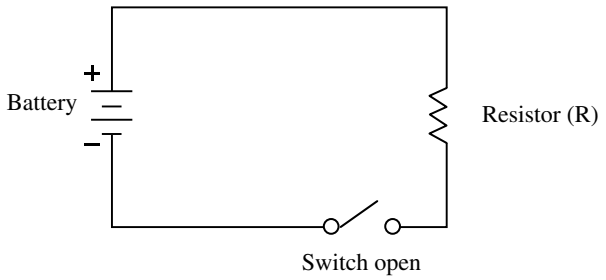

FIGURE 6.21 Open circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

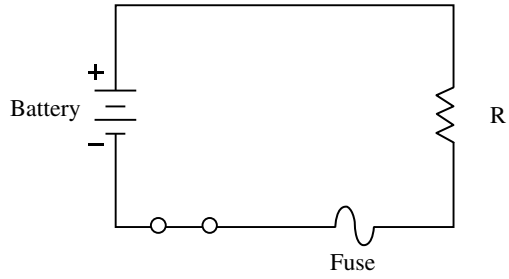

FIGURE 6.22 A simple fused circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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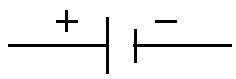

FIGURE 6.23 Schematic symbol for a battery. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

whenever a dangerous large current starts to flow (i.e., a short circuit condition occurs, caused by an accidental connection between two points in a circuit which offers very little resistance). A fuse will permit currents smaller than the fuse value to flow but will melt and therefore break or open the circuit if a larger current flows.

6.11.1 Schematic Representation

The simple circuits shown in Figure 6.20, Figure 6.21, and Figure 6.22 are displayed in schematic form. A schematic diagram (usually shortened to schematic) is a simplified drawing that represents the electrical, not the physical, situation in a circuit. The symbols used in schematic diagrams are the electrician's "shorthand;" they make the diagrams easier to draw and easier to understand. Consider the symbol in Figure 6.23 used to represent a battery power supply. The symbol is rather simple and straightforward, but is also very important. For example, by convention, the shorter line in the symbol for a battery represents the negative terminal. It is important to remember this because it is sometimes necessary to note the direction of current flow, which is from negative to positive, when you examine the schematic. The battery symbol shown in Figure 6.23 has a single cell; only one short and one long line are used. The number of lines used to represent a battery vary (and they are not necessarily equivalent to the number of cells), but they are always in pairs, with long and short lines alternating. In the circuit shown in Figure 6.22, the current would flow in a counterclockwise direction. If the long and short lines of the battery symbol (symbol shown in Figure 6.23) were reversed, the current in the circuit shown in Figure 6.22 would flow clockwise.

Note: In studies of electricity and electronics many circuits are analyzed which consist mainly of specially designed resistive components. As previously stated, these components are called **resistors**. Throughout the remaining analysis of the basic circuit, the resistive component will be a physical resistor. However, the resistive component could be any one of several electrical devices.

Keep in mind that in the simple circuits shown in the figures to this point we have only illustrated and discussed a few of the many symbols used in schematics to represent circuit components. (Other symbols will be introduced as we need them.)

It is also important to keep in mind that a closed loop of wire (conductor) is not necessarily a circuit. A source of voltage must be included to make it an electric circuit. In any electric circuit where electrons move around a closed loop, current, voltage, and resistance are present. The physical pathway for current flow is actually the circuit. By knowing any two of the three quantities, such as voltage and current, the third (resistance) may be determined. This is done mathematically using Ohm's law, the foundation on which electrical theory is based.

6.12 OHM'S LAW

Simply put, Ohm's law defines the relationship between current, voltage, and resistance in electric circuits. Ohm's law can be expressed mathematically in three ways.

1. The current in a circuit is equal to the voltage applied to the circuit divided by the resistance of the circuit. Stated another way, the current in a circuit is directly proportional to the applied voltage and inversely proportional to the circuit resistance. Ohm's law may be expressed as an equation:

$$I = \frac{E}{R} \tag{6.1}$$

where
I = current in amperes (A)
E = voltage (V)
R = resistance (Ω)

2. The resistance of a circuit is equal to the voltage applied to the circuit divided by the current in the circuit:

$$R = \frac{E}{I} \tag{6.2}$$

3. The applied voltage (E) to a circuit is equal to the product of the current and the resistance of the circuit:

$$E = I \times R = IR \tag{6.3}$$

If any two of the quantities in Equation 6.1 through Equation 6.3 are known, the third may be easily found. Let us look at an example.

Example 6.1

Problem:

Figure 6.24 shows a circuit containing a resistance of 6 Ω and a source of voltage of 3 V. How much current flows in the circuit?

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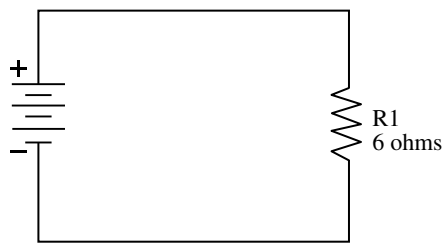

FIGURE 6.24 Determining current in a simple circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Given:

$E = 3\ V$
$R = 6\ \Omega$
$I = ?$

Solution:

$$I = \frac{E}{R}$$

$$= \frac{3}{6}$$

$$= 5\ A$$

To observe the effect of source voltage on circuit current, we use the circuit shown in Figure 6.24, but double the voltage to 6 V.

Notice that as the source of voltage doubles, the circuit current also doubles.

EXAMPLE 6.2

Problem:

Given:

$E = 6\ V$
$R = 6\ \Omega$
$I = ?$

Solution:

$$I = \frac{E}{R}$$

$$= \frac{6}{6}$$

$$= 1\ A$$

Key Point: Circuit current is directly proportional to applied voltage and will change by the same factor that the voltage changes.

To verify that current is inversely proportional to resistance, assume the resistor in Figure 6.24 to have a value of 12 Ω.

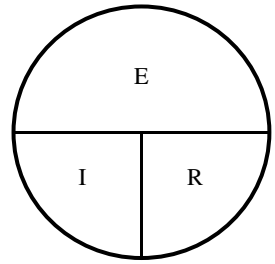

FIGURE 6.25 Ohm's law circle. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

EXAMPLE 6.3

Problem:

Given:

$E = 3$ volts
$R = 12\ \Omega$
$I = ?$

Solution:

$$I = \frac{E}{R}$$

$$= \frac{3}{12}$$

$$= 0.25\ A$$

Comparing this current of 0.25 A for the 12-Ω resistor, to the 0.5-A of current obtained with the 6-Ω resistor, shows that doubling the resistance will reduce the current to one half the original value. The point is that circuit current is inversely proportional to the circuit resistance.

Recall that if you know any two quantities, E and I, I and R, and E and R, you can calculate the third. In many circuit applications, current is known and either the voltage or the resistance will be the unknown quantity. To solve a problem, in which current and resistance are known, the basic formula for Ohm's law must be transposed to solve for E, I, or R.

However, the Ohm's law equations can be memorized and practiced effectively by using an Ohm's law circle (see Figure 6.25).

To find the equation for E, I, or R when two quantities, are known cover the unknown third quantity with your finger, ruler, a piece of paper etc., as shown in Figure 6.26.

EXAMPLE 6.4

Problem:

Find I when $E = 120\ V$ and $R = 40\ \Omega$.

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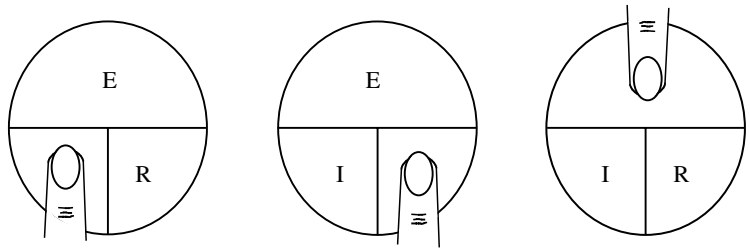


$$I = \frac{E}{R} \qquad R = \frac{E}{I} \qquad E = I \times R$$

FIGURE 6.26 Putting the Ohm's law circle to work. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Solution:

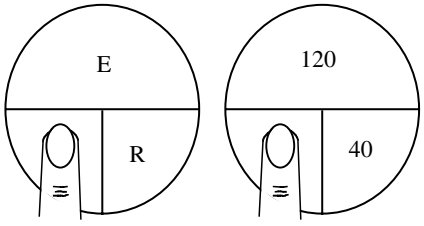
Place finger on I as shown in the figure below.

Use Equation 6.1 to find the unknown I:

$$I = \frac{E}{R}$$

$$= \frac{120}{40}$$

$$= 3A$$



EXAMPLE 6.5

Problem:

Find R when E = 220 V and I = 10 A

Solution:

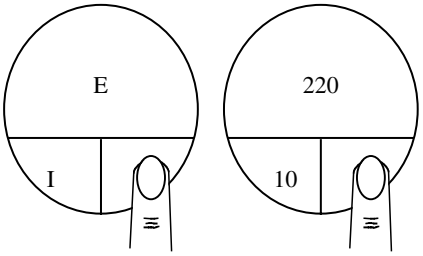
Place finger on R as shown in the figure.

Use Equation 6.2 to find the unknown R:

$$R = \frac{E}{I}$$

$$= \frac{220}{10}$$

$$= 22\ \Omega$$



EXAMPLE 6.6

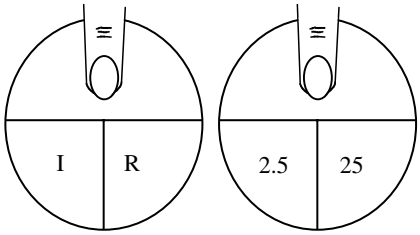
Problem:

Find E when I = 2.5 A and R = 25 Ω.

Solution:

Place finger on E as shown in the figure.

$$E = IR = 2.5(25) = 62.5\ V$$



Note: In the previous examples we have demonstrated how the Ohm's law circle can help solve simple voltage, current and amperage problems. Beginning students are cautioned not to rely wholly on the use of this circle when transposing simple formulas but rather to use it to supplement their knowledge of the algebraic method. Algebra is a basic tool in the solution of electrical problems and the importance of knowing how to use it should not be underemphasized or bypassed after the operator has learned a shortcut method such as the one indicated in this circle.

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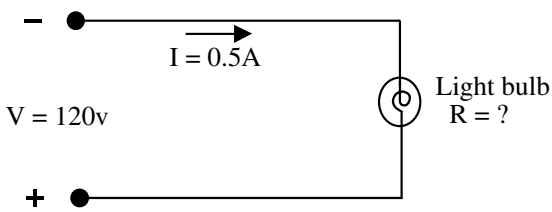

FIGURE 6.27 Simple circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

EXAMPLE 6.7

Problem:

An electric light bulb draws 0.5 A when operating on a 120-V DC circuit. What is the resistance of the bulb?

Solution:

The first step in solving a circuit problem is to sketch a schematic diagram of the circuit, labeling each of the parts and showing the known values (see Figure 6.27).

Since I and E are known, we use Equation 6.2 to solve for R:

$$R = \frac{E}{I}$$

$$= \frac{120}{0.5}$$

$$= 240\ \Omega$$

6.13 ELECTRICAL POWER

Power, whether electrical or mechanical, pertains to the rate at which work is being done. Therefore, the power consumption in your plant is related to current flow. A large electric motor or air dryer consumes more power (and draws more current) in a given length of time than, for example, an indicating light on a motor controller. Work is done whenever a force causes motion. If a mechanical force is used to lift or move a weight, work is done. Force exerted without causing motion, such as the force of a compressed spring acting between two fixed objects, does not constitute work.

Key Point: Power is the rate at which work is done.

6.13.1 ELECTRICAL POWER CALCULATIONS

The electric power P used in any part of a circuit is equal to the current I in that part multiplied by the V across that part of the circuit. In equation form:

$$P = E \times I \tag{6.4}$$

where

P = power (W)
E = voltage (V)
I = current (A)

If we know the current I and the resistance R, but not the voltage V, we can find the power P by using Ohm's law for voltage, so that substituting

$E = I \times R$ into Equation 6.4 we have:

$$P = I \times R \times I = I^2R \tag{6.5}$$

In the same manner, if we know the voltage V and the resistance R, but not the current I, we can find the P by using Ohm's law for current, so that substituting

$$I = \frac{E}{R}$$

into Equation 6.4 we have:

$$P = E \times \frac{E}{R} = \frac{E^2}{R} \tag{6.6}$$

Key Point: If we know any two quantities, we can calculate the third.

EXAMPLE 6.8

Problem:

The current through a 200-Ω resistor to be used in a circuit is 0.25 A. Find the power rating of the resistor.

Solution:

Since I and R are known, use Equation 6.5 to find P.

$$P = I^2 \times R$$

$$= 0.25^2 \times 200$$

$$= 0.0625 \times 200$$

$$= 12.5\ W$$

Important Point: The power rating of any resistor used in a circuit should be twice the wattage calculated by the power equation to prevent the resistor from burning out. Thus, the resistor used in Example 6.8 should have a power rating of 25 W.

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EXAMPLE 6.9

Problem:

How many kilowatts of power are delivered to a circuit by a 220-V generator that supplies 30 A to the circuit?

Solution:

Since V and I are given, use Equation 6.4 to find P:

$$P = E \times I$$
$$= 220 \times 30$$
$$= 6600 \text{ W}$$
$$= 6.6 \text{ kW}$$

EXAMPLE 6.10

Problem:

If the voltage across a 30,000-Ω resistor is 450 V, what is the power dissipated in the resistor?

Solution:

Since R and E are known, use Equation 6.6 to find P:

$$P = \frac{E^2}{R}$$
$$= \frac{450^2}{30,000}$$
$$= \frac{202,500}{30,000}$$
$$= 6.75 \text{ W}$$

In this section, P was expressed in terms of alternate pairs of the other three basic quantities, E, I, and R. In practice, you should be able to express any one of the three basic quantities, as well as P, in terms of any two of the others. Figure 6.28 is a summary of twelve basic formulas you should know. The four quantities, E, I, R, and P, are at the center of the figure.

Adjacent to each quantity are three segments. Note that in each segment, the basic quantity is expressed in terms of two other basic quantities, and no two segments are alike.

6.14 ELECTRICAL ENERGY

Energy (the mechanical definition) is defined as the ability to do work (energy and time are essentially the same and are expressed in identical units). Energy is expended when work is done because it takes energy to maintain a force when that force acts through a distance. The total energy expended to do a certain amount of work is equal to the working force multiplied by the distance through which the force moved to do the work.

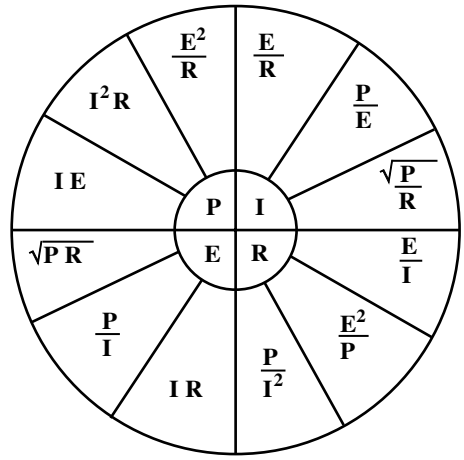

FIGURE 6.28 Ohm's law circle — Summary of basic formulas. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

In electricity, total energy expended is equal to the rate at which work is done, multiplied by the length of time the rate is measured. Essentially, energy W is equal to power P times time t.

The kilowatt-hour (kWh) is a unit commonly used for large amounts of electric energy or work. The amount of kilowatt-hours is calculated as the product of the power in kilowatts (kW) and the time in hours (h) during which the power is used:

$$\text{kWh} = \text{kW} \times \text{h} \tag{6.7}$$

EXAMPLE 6.11

Problem:

How much energy is delivered in 4 h by a generator supplying 12 kW?

Solution:

$$\text{kWh} = \text{kW} \times \text{h}$$
$$= 12 \times 4$$
$$= 48$$
$$\text{Energy delivered} = 48 \text{ kWh}$$

6.15 SERIES DC CIRCUIT CHARACTERISTICS

As previously mentioned, an electric circuit is made up of a voltage source, the necessary connecting conductors, and the effective load.

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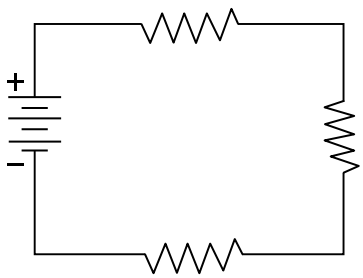

FIGURE 6.29 Series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

If the circuit is arranged so that the electrons have only one possible path, the circuit is called a Series circuit. Therefore, a series circuit is defined as a circuit that contains only one path for current flow. Figure 6.29 shows a series circuit having several loads (resistors).

Key Point: A series circuit is a circuit in which there is only one path for current to flow along.

6.15.1 Series Circuit Resistance

Referring to Figure 6.30, the current in a series circuit, in completing its electrical path, must flow through each resistor inserted into the circuit. Thus, each additional resistor offers added resistance. In a series circuit, the total circuit resistance (R_T) is equal to the sum of the individual resistances. As an equation:

$$R_T = R_1 + R_2 + R_3 \ldots R_n \tag{6.8}$$

where

R_T = total resistance (Ω)
R_1, R_2, R_3 = resistance in series (Ω)
R_n = any number of additional resistors in equation

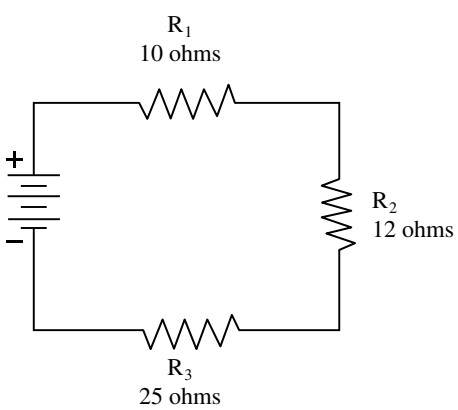

FIGURE 6.30 Solving for total resistance in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Example 6.12

Problem:

Three resistors of 10 Ω, 12 Ω, and 25 Ω are connected in series across a battery whose EMF is 110 V (Figure 6.30). What is the total resistance?

Solution:

Given:

$R_1 = 10\ \Omega$

$R_2 = 12\ \Omega$

$R_3 = 25\ \Omega$

$R_T = ?$

$$R_T = R_1 + R_2 + R_3$$

$$= 10 + 12 + 25$$

$$= 47\ \Omega$$

Equation 6.8 can be transposed to solve for the value of an unknown resistance. For example, transposition can be used in some circuit applications where the total resistance is known, but the value of a circuit resistor has to be determined.

Example 6.13

Problem:

The total resistance of a circuit containing 3 resistors is 50 Ω (see Figure 6.31). Two of the circuit resistors are 12 Ω each. Calculate the value of the third resistor.

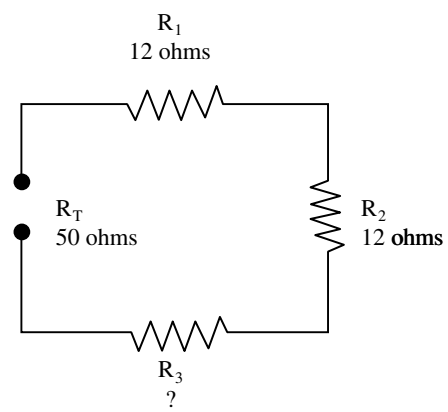

FIGURE 6.31 Calculating the value of one resistance in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Solution:

Given:

$$R_T = 50\ \Omega$$

$$R_1 = 12\ \Omega$$

$$R_2 = 12\ \Omega$$

$$R_3 = ?$$

Subtracting $(R_1 + R_2)$ from both sides of the equation:

$$R_T = R_1 + R_2 + R_3$$

$$R_3 = R_T - R_1 - R_2$$

$$R_3 = 50 - 12 - 12$$

$$R_3 = 50 - 24$$

$$R_3 = 26\ \Omega$$

Key Point: When resistances are connected in series, the total resistance in the circuit is equal to the sum of the resistances of all the parts of the circuit.

6.15.2 Series Circuit Current

Because there is but one path for current in a series circuit, the same *current* (I) must flow through each part of the circuit. Thus, to determine the current throughout a series circuit, only the current through one of the parts need be known.

The fact that the same current flows through each part of a series circuit can be verified by inserting ammeters into the circuit at various points as shown in Figure 6.32. As indicated in Figure 6.32, each meter indicates the same value of current.

Key Point: In a series circuit, the same current flows in every part of the circuit. Do not add the currents in each part of the circuit to obtain I.

6.15.3 Series Circuit Voltage

The voltage drop across the resistor in the basic circuit is the total voltage across the circuit and is equal to the applied voltage. The total voltage across a series circuit is also equal to the applied voltage, but consists of the sum of two or more individual voltage drops. This statement can be proven by an examination of the circuit shown in Figure 6.33.

In this circuit a source potential (E_T) of 30 V is impressed across a series circuit consisting of 2 6-Ω resistors. The total resistance of the circuit is equal to the sum of the two individual resistances, or 12 ohms. Using Ohm's law the circuit current may be calculated as follows:

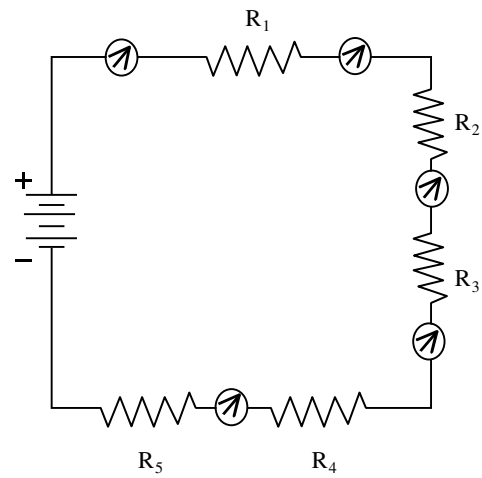

FIGURE 6.32 Current in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

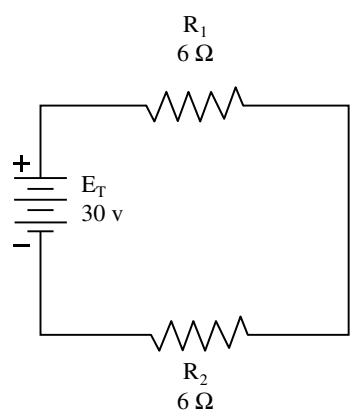

FIGURE 6.33 Calculating total resistance in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

$$I = \frac{E_T}{R_T}$$

$$= \frac{30}{12}$$

$$= 2.5\ \text{A}$$

Knowing the value of the resistors to be 6 Ω each, and the current through the resistors to be 2.5 A, the voltage drops across the resistors can be calculated. The voltage (E_1) across R_1 is therefore:

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$$E_1 = I \times R_1$$
$$= 2.5\ A \times 6\ \Omega$$
$$= 15\ V$$

Since R_2 is the same ohmic value as R_1 and carries the same current, the voltage drop across R_2 is also equal to 15 volts. Adding these 2 15-V drops together gives a total drop of 30 V exactly equal to the applied voltage. For a series circuit then,

$$E_T = E_1 + E_2 + E_3 \ldots E_n \tag{6.9}$$

where

E_T = total voltage (V)
E_1 = voltage across resistance R_1 (V)
E_2 = voltage across resistance R_2 (V)
E_3 = voltage across resistance R_3 (V)
E_4 = voltage across resistance R_n

Example 6.14

Problem:

A series circuit consists of 3 resistors having values of 10 Ω, 20 Ω, and 40 Ω, respectively. Find the applied voltage if the current through the 20-Ω resistor is 2.5 A.

Solution:

To solve this problem, a circuit diagram is first drawn and labeled as shown in Figure 6.34.

Given:

$R_1 = 10\ \Omega$
$R_2 = 20\ \Omega$
$R_3 = 40\ \Omega$
$I = 2.5\ A$

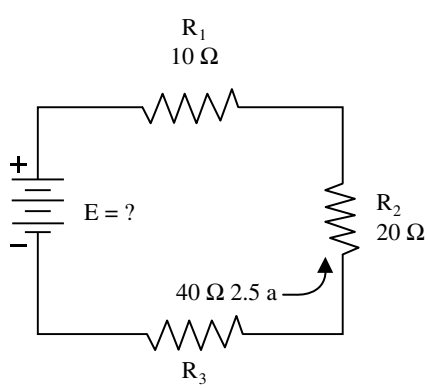

FIGURE 6.34 Solving for applied voltage in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Since the circuit involved is a series circuit, the same 2.5 A of current flows through each resistor. Using Ohm's law, the voltage drops across each of the three resistors can be calculated and are:

$E_1 = 25\ V$
$E_2 = 50\ V$
$E_3 = 100\ V$

Once the individual drops are known they can be added to find the total or applied voltage-using Equation 6.9:

$$E_T = E_1 + E_2 + E_3$$
$$= 25\ V + 50\ V + 100\ V$$
$$= 175\ V$$

Key Point 1: The total voltage (E_T) across a series circuit is equal to the sum of the voltages across each resistance of the circuit.

Key Point 2: The voltage drops that occur in a series circuit are in direct proportions to the resistance across which they appear. This is the result of having the same current flow through each resistor. The larger the resistor, the larger will be the voltage drop across it.

6.15.4 Series Circuit Power

Each resistor in a series circuit consumes *power.* This power is dissipated in the form of heat. Because this power must come from the source, the total power must be equal in amount to the power consumed by the circuit resistances. In a series circuit, the total power is equal to the sum of the powers dissipated by the individual resistors. Total power (P_T) is thus equal to:

$$P_T = P_1 + P_2 + P_3 \ldots P_n \tag{6.10}$$

where

P_T = total power (W)
P_1 = power used in first part (W)
P_2 = power used in second part (W)
P_3 = power used in third part (W)
P_n = power used in *n*th part (W)

Example 6.15

Problem:

A series circuit consists of three resistors having values of 5 Ω, 15 Ω, and 20 Ω. Find the total power dissipation when 120 V is applied to the circuit (see Figure 6.35).

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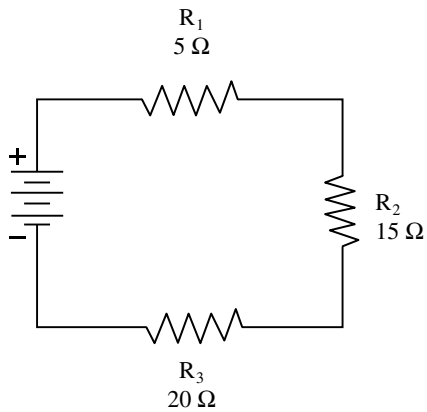

FIGURE 6.35 Solving for total power in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Solution:

Given:

$R_1 = 5\ \Omega$
$R_2 = 15\ \Omega$
$R_3 = 20\ \Omega$
$E = 120\ V$

The total resistance is found first:

$$R_T = R_1 + R_2 + R_3$$
$$= 5 + 15 + 20$$
$$= 40\ \Omega$$

Using total resistance and the applied voltage, the circuit current is calculated:

$$I = \frac{E_T}{R_T}$$
$$= \frac{120}{40}$$
$$= 3\ A$$

Using the power formula, the individual power dissipations can be calculated:

For resistor R_1:

$$P_1 = I^2 \times R_1$$
$$= 3^2 \times 5$$
$$= 45\ W$$

For R_2:

$$P_2 = I^2 \times R_2$$
$$= 3^2 \times 15$$
$$= 135\ W$$

For R_3:

$$P_3 = I^2 \times R_3$$
$$= 3^2 \times 20$$
$$= 180\ W$$

To obtain total power:

$$P_T = P_1 + P_2 + P_3$$
$$= 45 + 135 + 180$$
$$= 360\ W$$

To check the answer the total power delivered by the source can be calculated:

$$P = E \times I$$
$$= 3\ A \times 120\ V$$
$$= 360\ W$$

Thus, the total power is equal to the sum of the individual power dissipations.

Key Point: We found that Ohm's law can be used for total values in a series circuit as well as for individual parts of the circuit. Similarly, the formula for power may be used for total values:

$$P_T = I \times E_T \tag{6.11}$$

6.15.5 Summary of the Rules for Series DC Circuits

To this point, we have covered many of the important factors governing the operation of basic series circuits. In essence, what we have really done is to lay a strong foundation to build upon in preparation for more advanced circuit theory that follows. A summary of the important factors governing the operation of a series circuit are listed as follows:

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1. The same current flows through each part of a series circuit.
2. The total resistance of a series circuit is equal to the sum of the individual resistances.
3. The total voltage across a series circuit is equal to the sum of the individual voltage drops.
4. The voltage drop across a resistor in a series circuit is proportional to the size of the resistor.
5. The total power dissipated in a series circuit is equal to the sum of the individual dissipations.

6.15.6 General Series Circuit Analysis

Now that we have discussed the pieces involved in putting together the puzzle for solving series circuit analysis, we move on to the next step in the process: solving series circuit analysis in total.

Example 6.16

Problem:

Three resistors of 20 Ω, 20 Ω, and 30 Ω are connected across a battery supply rated at 100 V terminal voltage. Completely solve the circuit shown in Figure 6.36.

Note: In solving the circuit, the total resistance will be found first. Next, the circuit current will be calculated. Once the current is known the voltage drops and power dissipations can be calculated.

Solution:

The total resistance is:

$$R_T = R_1 + R_2 + R_3$$
$$= 20\ \Omega + 20\ \Omega + 30\ \Omega$$
$$= 70\ \Omega$$

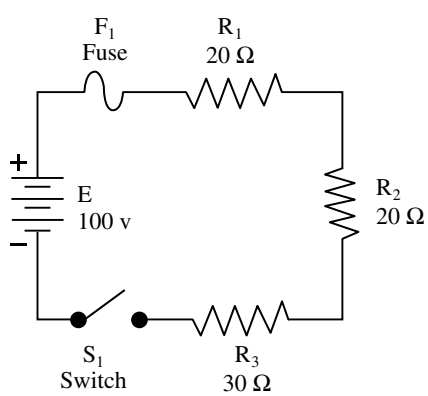

FIGURE 6.36 Solving for various values in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

By Ohm's law the current is:

$$I = \frac{E_T}{R_T}$$
$$= \frac{100}{70}$$
$$= 1.43\ \text{A (rounded)}$$

The voltage (E_1) across R_1 is:

$$E_1 = I \times R_1$$
$$= 1.43\ \text{A} \times 20\ \Omega$$
$$= 28.6\ \text{V}$$

The voltage (E_2) across R_2 is:

$$E_2 = I \times R_2$$
$$= 1.43\ \text{A} \times 20\ \Omega$$
$$= 28.6\ \text{V}$$

The voltage (E_3) across R_3 is:

$$E_3 = I \times R_2$$
$$= 1.43\ \text{A} \times 30\ \Omega$$
$$= 42.9\ \text{V}$$

The power dissipated by R_1 is:

$$P_1 = I \times E_1$$
$$= 1.43\ \text{A} \times 28.6\ \text{V}$$
$$= 40.9\ \text{W}$$

The power dissipated by R_2 is:

$$P_2 = I \times E_2$$
$$= 1.43\ \text{A} \times 28.6\ \text{V}$$
$$= 40.9\ \text{W}$$

The power dissipated by R_3 is:

$$P_3 = I \times E_3$$
$$= 1.43\ \text{A} \times 42.9\ \text{V}$$
$$= 61.3\ \text{W (rounded)}$$

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The total power dissipated is:

$$P_T = E_T \times I$$
$$= 100\ V \times 1.43\ A$$
$$= 143\ W$$

Note: Keep in mind when applying Ohm's law to a series circuit to consider whether the values used are component values or total values. When the information available enables the use of Ohm's law to find total resistance, total voltage and total current, total values must be inserted into the formula.

To find total resistance:

$$R_T = \frac{E_T}{I_T}$$

To find total voltage:

$$E_T = I_T \times R_T$$

To find total current:

$$I_T = \frac{E_T}{R_T}$$

6.15.6.1 Kirchhoff's Voltage Law

Kirchhoff's voltage law states that the voltage applied to a closed circuit equals the sum of the voltage drops in that circuit. It should be obvious that this fact was used in the study of series circuits to this point. It was expressed as follows:

Voltage applied = sum of voltage drops

$$E_A = E_1 + E_2 + E_3$$

where

E_A = the applied voltage
E_1 = voltage drop
E_2 = voltage drop
E_3 = voltage drop

Another way of stating Kirchhoff's law is that the algebraic sum of the instantaneous EMFs and voltage drops around any closed circuit is zero.

Through the use of Kirchhoff's law, circuit problems can be solved that would be difficult and often impossible with only knowledge of Ohm's law. When Kirchhoff's law is properly applied, an equation can be set up for a closed loop and the unknown circuit values may be calculated.

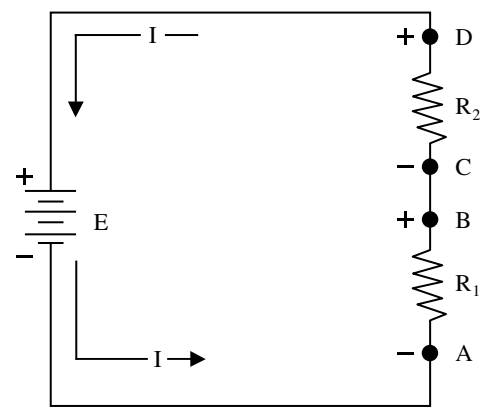

FIGURE 6.37 Polarity of voltage drops. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.15.6.1.1 Polarity of Voltage Drops

When there is a voltage drop across a resistance, one end must be more positive or more negative than the other end. The polarity of the voltage drop is determined by the direction of current flow. In the circuit shown in Figure 6.37, the current is seen to be flowing in a counterclockwise direction due to the arrangement of the battery source E. Notice that the end of resistor R_1 into which the current flows is marked negative (–). The end of R_1 at which the current leaves is marked positive (+). These polarity markings are used to show that the end of R_1 into which the current flows is at a higher negative potential than is the end of the resistor at which the current leaves. Point A is thus more negative than point B.

Point C, which is at the same potential as point B, is labeled negative. This is to indicate that point C, though positive with respect to point A, is more negative than point D. To say a point is positive (or negative), without stating what it is positive in respect to, has no meaning.

Kirchhoff's voltage law can be written as an equation as shown below:

$$E_a + E_b + E_c + \ldots E_n = 0 \qquad (6.12)$$

where

E_a = voltage drop and EMF around any closed circuit loop
E_b = voltage drops and EMF around any closed circuit loop
E_c = voltage drop and EMF around any closed circuit loop
E_n = additional voltage drops and EMF around any closed circuit loop

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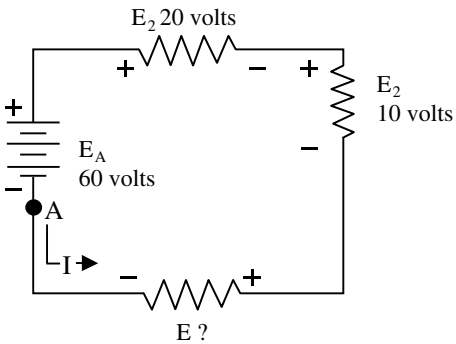

FIGURE 6.38 Determining unknown voltage in a series circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

EXAMPLE 6.17

Problem:

Three resistors are connected across a 60-V source. What is the voltage across the third resistor if the voltage drops across the first two resistors are 10 V and 20 V?

Solution:

First, draw a diagram like the one shown in Figure 6.38. Next, a direction of current is assumed as shown. Using this current, the polarity markings are placed at each end of each resistor and on the terminals of the source. Starting at point A, trace around the circuit in the direction of current flow recording the voltage and polarity of each component. Starting at point A these voltages would be as follows:

Basic formula:

$$E_a + E_b + E_c \ldots E_n = 0$$

From the circuit:

$$(+E_x) + (+E_2) + (+E_3) - (E_A) = 0$$

Substituting values from circuit:

$$E_x + 10 + 20 - 60 = 0$$

$$E_x - 30 = 0$$

$$E_x = 30 \text{ V}$$

Thus, the unknown voltage (E_x) is found to be 30 V.

Note: Using the same idea as above, a problem can be solved in which the current is the unknown quantity.

6.15.6.1.2 Series Aiding and Opposing Sources

Sources of voltage that cause current to flow in the same direction are considered to be series aiding, and their voltages are added. Sources of voltage that would tend to force current in opposite directions are said to be series opposing, and the effective source voltage is the difference between the opposing voltages. When two opposing sources are inserted into a circuit, current flow would be in a direction determined by the larger source. Examples of series aiding and opposing sources are shown in Figure 6.39.

6.15.6.1.3 Kirchhoff's Law and Multiple Source Solutions

Kirchhoff's law can be used to solve multiple source circuit problems. In applying this method, the exact same procedure is used for multiple source circuits as was used for single source circuits. This is demonstrated by the following example:

EXAMPLE 6.18

Problem:

Find the amount of current in the circuit shown in Figure 6.40.

Solution:

Start at point A.

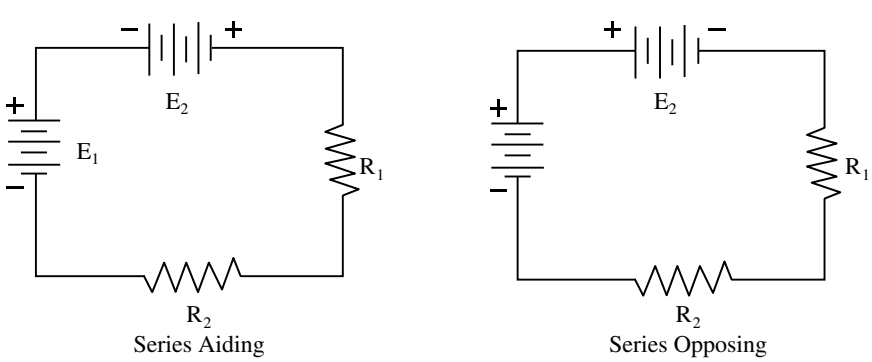

FIGURE 6.39 Aiding and opposing sources. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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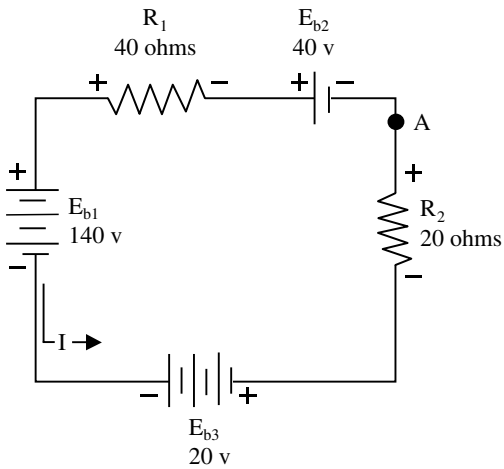

FIGURE 6.40 Solving for circuit current in a multiple source circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Basic equation:

$$E_a + E_b + E_c + \ldots E_n = 0$$

From the circuit:

$$E_{b2} + E_1 - E_{b1} + E_{b3} + E_2 = 0$$

$$40 + (40 \times I) - 140 + 20 + (20 \times I) = 0$$

Combining like terms:

$$(60 \times I) - 80 = 0$$

$$60 \times I = 80$$

$$I = 1.33 \text{ A}$$

6.16 GROUND

The term ground is used to denote a common electrical point of zero potential. The reference point of a circuit is always considered to be at zero potential, since the earth (ground) is said to be at a zero potential. In Figure 6.41, point A is the zero reference or ground and is symbolized as such. Point C is 60 V positive and point B is 20 V positive in respect to ground.

The common ground for much electrical or electronic equipment is the metal chassis. The value of ground is noted when considering its contribution to economy, simplification of schematics, and ease of measurement. When completing each electrical circuit, common points of a circuit at zero potential are connected directly to the metal chassis, eliminating a large amount of connecting wire. An example of a grounded circuit is illustrated in Figure 6.42.

Note: Most voltage measurements used to check proper circuit operation in electronic equipment are taken in respect to ground. One-meter lead is attached to ground and the other meter lead is moved to various test points.

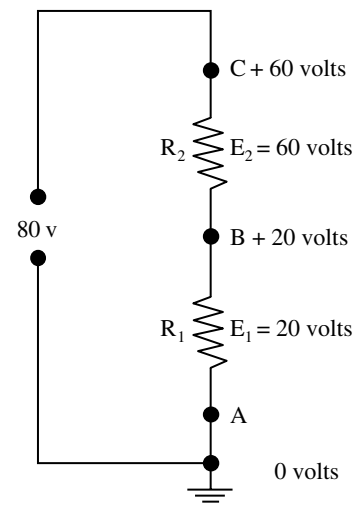

FIGURE 6.41 Use of ground symbols. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

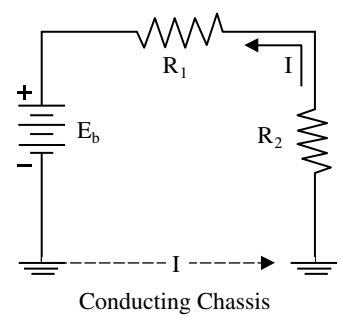

FIGURE 6.42 Ground used as a conductor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.17 OPEN AND SHORT CIRCUITS

A circuit is open if a break in the circuit does not provide a complete path for current. Figure 6.43 shows an open circuit, because the fuse is blown.

To protect a circuit, a fuse is placed directly into the circuit. A fuse will open the circuit whenever a dangerously large current starts to flow. A fuse will permit currents smaller than the fuse value to flow, but will melt and break or open the circuit if a larger current flows. A dangerously large current will flow when a short circuit occurs. A short circuit is usually caused by an accidental connection between two points in a circuit that offers very little resistance that passes an abnormal amount of current. A short circuit often occurs because of improper wiring or broken insulation.

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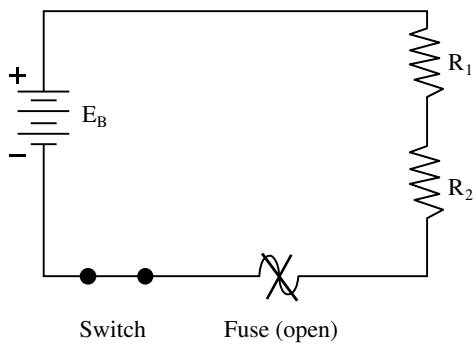

FIGURE 6.43 Open circuit — fuse blown. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.18 PARALLEL DC CIRCUITS

The principles we applied to solving simple series circuit calculations for determining the reactions of such quantities as voltage, current, and resistance can be used in parallel and series-parallel circuits.

6.18.1 Parallel Circuit Characteristics

A parallel circuit is defined as a circuit that has two or more components connected across the same voltage source (see Figure 6.44). Recall that in a series circuit there is only one path for current flow. As additional loads (resistors, etc.) are added to the circuit, the total resistance increases and the total current decreases. This is not the case in a parallel circuit. In a parallel circuit, each load (or branch) is connected directly across the voltage source. In Figure 6.44, commencing at the voltage source (E_b) and tracing counterclockwise around the circuit, two complete and separate paths can be identified in which current can flow. One path is traced from the source through resistance R_1 and back to the source; the other is traced from the source through resistance R_2 and back to the source.

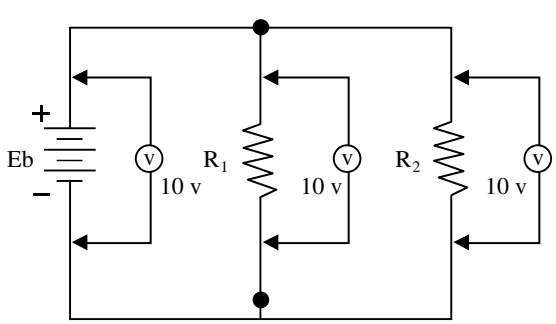

FIGURE 6.45 Voltage comparison in a parallel circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

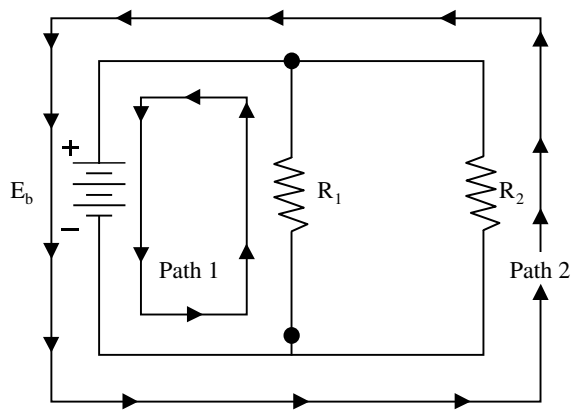

FIGURE 6.44 Basic parallel circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.18.2 Voltage in Parallel Circuits

Recall that in a series circuit the source voltage divides proportionately across each resistor in the circuit. In a parallel circuit (see Figure 6.44), the same voltage is present across all the resistors of a parallel group. This voltage is equal to the applied voltage (E_b) and can be expressed in equation form as:

$$E_b = E_{R_1} = E_{R_2} = E_{R_n} \tag{6.13}$$

We can verify Equation 6.13 by taking voltage measurements across the resistors of a parallel circuit, as illustrated in Figure 6.45. Notice that each voltmeter indicates the same amount of voltage; the voltage across each resistor is the same as the applied voltage.

Key Point: In a parallel circuit the voltage remains the same throughout the circuit.

Example 6.19

Problem:

Assume that the current through a resistor of a parallel circuit is known to be 4.0 mA and the value of the resistor is 40,000 Ω. Determine the potential (voltage) across the resistor. The circuit is shown in Figure 6.46.

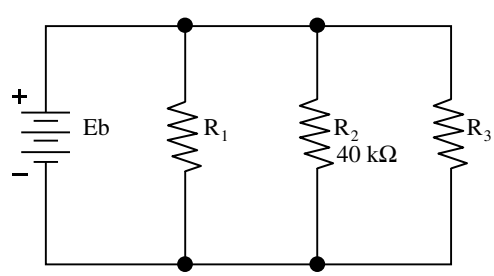

FIGURE 6.46 For Example 3.19. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Solution:

Given:

$R_2 = 40\ k\Omega$
$I_{R_2} = 4.0\ mA$

Find:

$E_{R_2} = x$
$E_b = x$

Select the proper equation:

$$E = I \times R$$

Substitute known values:

$$E_{R_2} = I_{R_2} \times R_2$$

$$4.0\ mA \times 40{,}000\ \Omega$$

(use power of tens)

$$E_{R2} = (4.0 \times 10^{-3}) \times (40 \times 10^{3})$$

$$= 4.0 \times 40$$

$$= 160\ V$$

Therefore, $E_b = 160$ V

6.18.3 Current in Parallel Circuits

Important Point: Ohm's law states, the current in a circuit is inversely proportional to the circuit resistance. This fact, important as a basic building block of electrical theory, is also important in the following explanation of current flow in parallel circuits.

In a series circuit, a single current flows. Its value is determined in part by the total resistance of the circuit. However, the source current in a parallel circuit divides among the available paths in relation to the value of the resistors in the circuit. Ohm's law remains unchanged. For a given voltage, current varies inversely with resistance.

The behavior of current in a parallel circuit is best illustrated by example. The example we use is Figure 6.47. The resistors R_1, R_2, and R_3 are in parallel with each other and with the battery. Each parallel path is then a branch with its own individual current. When the total current I_T leaves the voltage source E, part I_1 of the current I_T will flow through R_1, part I_2 will flow through R_2, and the remainder I_3 through R_3. The branch current I_1, I_2, and I_3 can be different. However, if a voltmeter (used for measuring the voltage of a circuit) is connected across R_1, R_2, and R_3, the respective voltages E_1, E_2, and E_3 will be equal. Therefore:

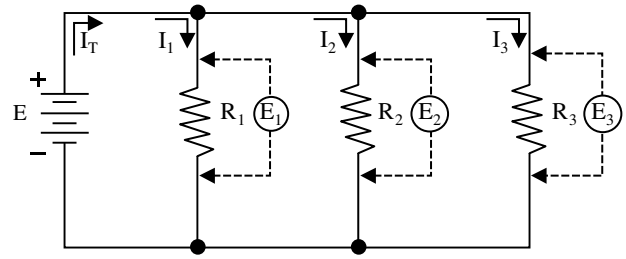

FIGURE 6.47 Parallel circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

$$E = E_1 = E_2 = E_3 \tag{6.14}$$

The total current I_T is equal to the sum of all branch currents:

$$I_T = I_1 + I_2 + I_3 \tag{6.15}$$

This formula applies for any number of parallel branches whether the resistances are equal or unequal.

By Ohm's law, each branch current equals the applied voltage divided by the resistance between the two points where the voltage is applied. Hence for each branch we have the following equations:

$$\text{Branch 1: } I_1 = \frac{E_1}{R_1} = \frac{E}{R_1}$$

$$\text{Branch 2: } I_2 = \frac{E_2}{R_2} = \frac{E}{R_2} \tag{6.16}$$

$$\text{Branch 3: } I_3 = \frac{E_3}{R_3} = \frac{E}{R_3}$$

With the same applied voltage, any branch that has less resistance allows more current through it than a branch with higher resistance.

Example 6.20

Problem:

Two resistors each drawing 2 A and a third resistor drawing 1 A are connected in parallel across a 100-V line (see Figure 6.48). What is the total current?

Solution:

The formula for total current is:

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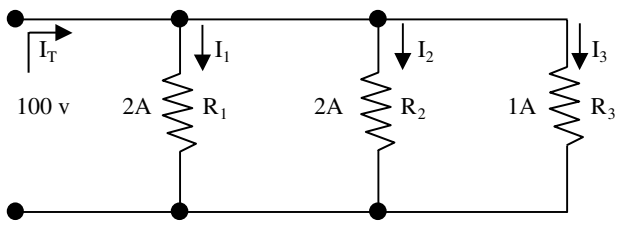

FIGURE 6.48 For Example 6.20. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

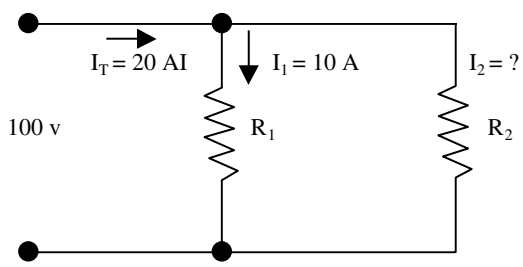

FIGURE 6.49 For Example 6.21. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

$$I_T = I_1 + I_2 + I_3$$
$$= 2 + 2 + 1$$
$$= 5 \text{ A}$$

The total current is 5 A.

Example 6.21

Problem:

Two branches, R_1 and R_2, across a 100-V power line draw a total line current of 20 A (Figure 6.49). Branch R_1 takes 10 A. What is the current I_2 in branch R_2?

Solution:

Starting with Equation 6.15, transpose to find I_2 and then substitute given values:

$$I_T = I_1 + I_2$$
$$I_2 = I_T - I_1$$
$$= 20 - 10$$
$$= 10 \text{ A}$$

The current in branch R_2 is 10 A.

Example 6.22

Problem:

A parallel circuit consists of 2 15-Ω and one 12-Ω resistor across a 120-V line (see Figure 6.50). What current will flow in each branch of the circuit and what is the total

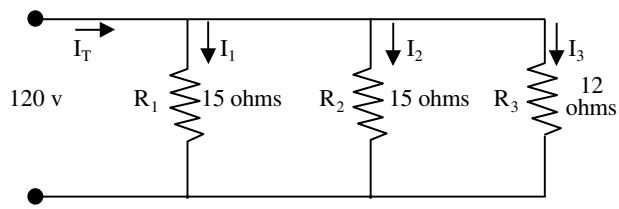

FIGURE 6.50 For Example 6.22. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Solution:

There is 120-V potential across each resistor. Using Equation 6.16, apply Ohm's law to each resistor:

$$I_1 = \frac{E_1}{R_1} = \frac{120}{15} = 8 \text{ A}$$

$$I_2 = \frac{E_2}{R_2} = \frac{120}{15} = 8 \text{ A}$$

$$I_3 = \frac{E_3}{R_3} = \frac{120}{12} = 10 \text{ A}$$

Now find total current, using Equation 6.15:

$$I_T = I_1 + I_2 + I_3$$
$$= 8 + 8 + 10$$
$$= 26 \text{ A}$$

6.18.4 Parallel Circuits and Kirchhoff's Current Law

The division of current in a parallel network follows a definite pattern. This pattern is described by Kirchhoff's current law, which is stated as follows: the algebraic sum of the currents entering and leaving any junction of conductors is equal to zero. This can be stated mathematically as:

$$I_a + I_b + \ldots + I_n = 0 \qquad (6.17)$$

where

I_a = current entering and leaving the junction
I_b = current entering and leaving the junction
I_n = additional currents entering and leaving the junction

Currents entering the junction are assumed positive, and currents leaving the junction are considered negative. When solving a problem using Equation 6.17, the currents must be placed into the equation with the proper polarity.

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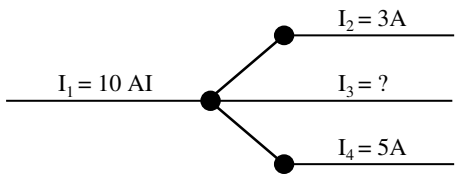

FIGURE 6.51 For Example 6.23. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

EXAMPLE 6.23

Problem:

Solve for the value of I_3 in Figure 6.51.

Solution:

First, the currents are given proper signs:

$I_1 = +10$ A
$I_2 = -3$ A
$I_3 = x$ A
$I_4 = -5$ A

Then, place these currents into Equation 6.17 with the proper signs as follows:

Basic equation:

$$I_a + I_b + \ldots I_n = 0$$

Substitution:

$$I_1 + I_2 + I_3 + I_4 = 0$$

$$(+10) + (-3) + (I_3) + (-5) = 0$$

Combining like terms:

$$I_3 + 2 = 0$$

$$I_3 = -2 \text{ amps}$$

Thus, I_3 has a value of 2 A, and the negative sign shows it to be a current leaving the junction.

6.18.5 PARALLEL CIRCUIT RESISTANCE

Unlike series circuits, where total resistance (R_T) is the sum of the individual resistances, in a parallel circuit the total resistance is not the sum of the individual resistances.

In a parallel circuit, we can use Ohm's law to find total resistance. We use the equation:

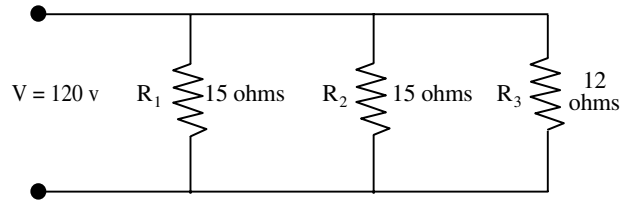

FIGURE 6.52 For Example 6.24. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

$$R = \frac{E}{I}$$

or

$$R_T = \frac{E_S}{I_T}$$

where
R_T = the total resistance of all the parallel branches across the voltage source
E_S = voltage source
I_T = sum of all the branch currents

EXAMPLE 6.24

Problem:

What is the total resistance of the circuit shown in Figure 6.52?

Given:

$E_S = 120$ V
$I_T = 26$ A

Solution:

In Figure 6.52, the line voltage is 120 V and the total line current is 26 A. Therefore:

$$R_T = \frac{E_S}{I_T}$$

$$= \frac{120}{26}$$

$$= 4.62\ \Omega$$

Important Point: Notice that R_T is smaller than any of the three resistances in Figure 6.52. This fact may surprise you — it may seem strange that the total circuit resistance is less than that of the smallest resistor (R_3-12 Ω). However, if we refer back to the water analogy we have used previously, it makes sense. Consider water

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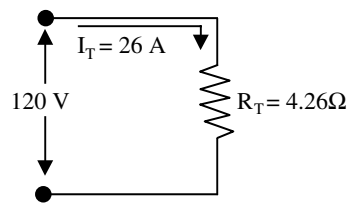

FIGURE 6.53 Equivalent circuit to that of Figure 6.52. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

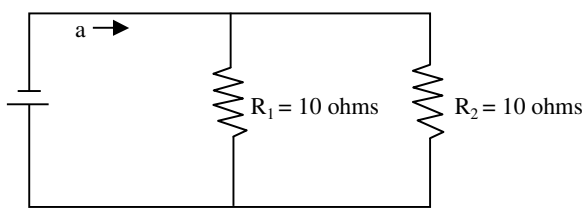

FIGURE 6.54 Two equal resistors connected in parallel. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

pressure and water pipes, and assume there is some way to keep the water pressure constant. A small pipe offers more resistance to flow of water than a larger pipe. However, if we add another pipe in parallel, one of even smaller diameter, the total resistance to water flow is decreased. In an electrical circuit, even a larger resistor in another parallel branch provides an additional path for current flow, so the total resistance is less. Remember, if we add one more branch to a parallel circuit, the total resistance decreases and the total current increases.

Refer to Example 6.24 and Figure 6.52. What we essentially demonstrated in working this particular problem is that the total load connected to the 120-V line is the same as the single equivalent resistance of 4.62 Ω connected across the line. (It is probably more accurate to call this total resistance the equivalent resistance, but by convention R_t, or total resistance, is used — but they are often used interchangeably, too.)

We illustrate the equivalent resistance in the equivalent circuit shown in Figure 6.53.

There are other methods used to determine the equivalent resistance of parallel circuits. The most appropriate method for a particular circuit depends on the number and value of the resistors. For example, consider the parallel circuit shown in Figure 6.54.

For this circuit, the following simple equation is used:

$$R_{eq} = \frac{R}{N} \tag{6.18}$$

where

R_{eq} = equivalent parallel resistance
R = ohmic value of one resistor
N = number of resistors

Thus,

$$R_{eq} = \frac{10\ \Omega}{2}$$
$$= 5\ \Omega$$

Note: Equation 6.18 is valid for any number of equal value parallel resistors.

Key Point: When two equal value resistors are connected in parallel, they present a total resistance equivalent to a single resistor of one-half the value of either of the original resistors.

EXAMPLE 6.25

Problem:

Five 50-Ω resistors are connected in parallel. What is the equivalent circuit resistance?

Solution:

Using Equation 6.18

$$R_{eq} = \frac{R}{N}$$
$$= \frac{50\ \Omega}{5}$$
$$= 10\ \Omega$$

What about parallel circuits containing resistance of unequal value? How is equivalent resistance determined? Example 6.26 demonstrates how this is accomplished.

EXAMPLE 6.26

Problem:

Refer to Figure 6.55.

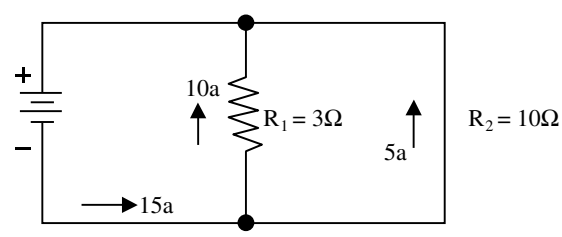

FIGURE 6.55 For Example 6.26. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Solution:

Given:

$R_1 = 3\ \Omega$
$R_2 = 6\ \Omega$
$E_a = 30\ V$

Known:

$I_1 = 10\ A$
$I_2 = 5\ A$
$I_T = 15\ A$

Determine R_{eq}.

$$R_{eq} = \frac{E_a}{I_T}$$

$$= \frac{30}{15}$$

$$= 2\ \Omega$$

Key Point: In Example 6.26 the equivalent resistance of 2 Ω is less than the value of either branch resistor. Remember, in parallel circuits the equivalent resistance will always be smaller than the resistance of any branch.

6.18.5.1 Reciprocal Method

When circuits are encountered in which resistors of unequal value are connected in parallel, the equivalent resistance may be computed by using the reciprocal method.

Note: A reciprocal is an inverted fraction; the reciprocal of the fraction 3/4, for example is 4/3. We consider a whole number to be a fraction with 1 as the denominator, so the reciprocal of a whole number is that number divided into 1. For example, the reciprocal of R_T is $1/R_T$.

The equivalent resistance in parallel is given by the formula:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n} \qquad (6.19)$$

where
R_T = the total resistance in parallel
R_1 = branch resistance
R_2 = branch resistance
R_3 = branch resistance
R_n = additional branch resistances.

EXAMPLE 6.27

Problem:

Find the total resistance of a 2-Ω, a 4-Ω, and an 8-Ω resistor in parallel (Figure 6.56).

Solution:

Write the formula for three resistors in parallel:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Substituting the resistance values:

$$\frac{1}{R_T} = \frac{1}{2} + \frac{1}{4} + \frac{1}{8}$$

Add fractions:

$$\frac{1}{R_T} = \frac{4}{8} + \frac{2}{8} + \frac{1}{8} = \frac{7}{8}$$

Invert both sides of the equation to solve for R_T:

$$R_T = \frac{8}{7}$$

$$= 1.14\ \Omega$$

Note: When resistances are connected in parallel, the total resistance is always **less** than the smallest resistance of any single branch.

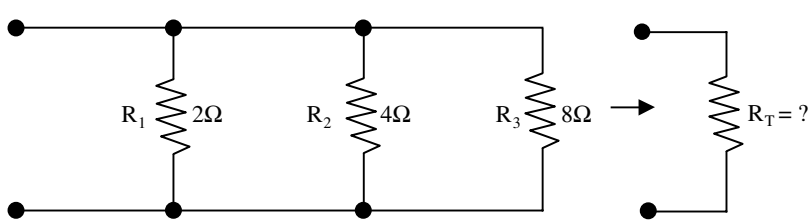

FIGURE 6.56 For Example 6.27. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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6.18.5.2 Product over the Sum Method

When any two unequal resistors are in parallel, it is often easier to calculate the total resistance by multiplying the two resistances and then dividing the product by the sum of the resistances.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} \tag{6.20}$$

where

R_T = the total resistance in parallel
R_1 = the resistor in parallel
R_2 = the two resistors in parallel

EXAMPLE 6.28

Problem:

What is the equivalent resistance of a 20-Ω and a 30-Ω resistor connected in parallel?

Solution:

Given:

$R_1 = 20$
$R_2 = 30$

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{20 \times 30}{20 + 30} = 12\ \Omega$$

6.18.5.3 Reduction to an Equivalent Circuit

In the study of basic electricity, it is often necessary to resolve a complex circuit into a simpler form. Any complex circuit consisting of resistances can be reduced to a basic equivalent circuit containing the source and total resistance. This process is called reduction to an equivalent circuit. An example of circuit reduction was demonstrated in Example 6.28 and is illustrated in Figure 6.57.

The circuit shown in Figure 6.57-A is reduced to the simple circuit shown in Figure 6.57-B.

6.18.6 POWER IN PARALLEL CIRCUITS

As in the series circuit, the total power consumed in a parallel circuit is equal to the sum of the power consumed in the individual resistors:

Note: Because power dissipation in resistors consists of a heat loss, power dissipations are additive regardless of how the resistors are connected in the circuit.

$$P_T = P_1 + P_2 + P_3 + \ldots + P_n \tag{6.21}$$

where

P_T = the total power
P_1 = branch power
P_2 = branch power
P_3 = branch power
P_n = additional branch powers

Total power can also be calculated by the equation:

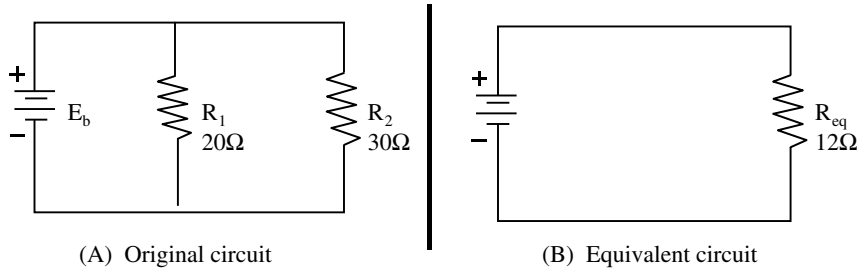
$$P_T = E \times I_T \tag{6.22}$$

where

P_T = total power
E = voltage source across all parallel branches
I_T = the total current

The power dissipated in each branch is equal to EI and equal to V^2/R.

Note: In both parallel and series arrangements, the sum of the individual values of power dissipated in the circuit is equal to the total power generated by the source. The circuit arrangements cannot change the fact that all power in the circuit comes from the source.



(A) Original circuit (B) Equivalent circuit

FIGURE 6.57 Parallel circuit with equivalent circuit. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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6.18.7 Rules for Solving Parallel DC Circuits

Problems involving the determination of resistance, voltage, current, and power in a parallel circuit are solved as simply as in a series circuit. The procedure is the same:

1. Draw a circuit diagram
2. State the values given and the values to be found
3. State the applicable equations
4. Substitute the given values and solve for the unknown

Along with following the problem-solving procedure above, it is also important to remember and apply the rules for solving parallel DC circuits. These rules are:

1. The same voltage exists across each branch of a parallel circuit and is equal to the source voltage.
2. The current through a branch of a parallel network is inversely proportional to the amount of resistance of the branch.
3. The total current of a parallel circuit is equal to the sum of the currents of the individual branches of the circuit.
4. The total resistance of a parallel circuit is equal to the reciprocal of the sum of the reciprocals of the individual resistances of the circuit.
5. The total power consumed in a parallel circuit is equal to the sum of the power consumption of the individual resistances.

6.19 SERIES-PARALLEL CIRCUITS

To this point, we have discussed series and parallel DC circuits. Operators will seldom encounter a circuit that consists solely of either type of circuit. Most circuits consist of both series and parallel elements. A circuit of this type is referred to as a series-parallel circuit, or as a combination circuit. The solution of a series-parallel (combination) circuit is simply a matter of application of the laws and rules discussed before this point.

6.19.1 Solving a Series-Parallel Circuit

At least three resistors are required to form a series-parallel circuit. An example of a series-parallel circuit is shown in Figure 6.58, where two parallel resistors, R_2 and R_3, are connected in series with the resistor R_1 and the voltage source E. In a circuit of this type, the current I_T divides after it flows through R_1, and part flows through R_2 and part flows through R_3. Then the current joins at the junction of the two resistors and flows back to the positive terminal of the voltage source and through the voltage source to the positive terminal.

In solving for values in a series-parallel circuit (current, voltage, and resistance), follow the rules that apply to a series circuit for the series part of the circuit, and follow the rules that apply to a parallel circuit for the parallel part of the circuit. Solving series-parallel circuits is simplified if all parallel and series groups are first reduced to single equivalent resistances and the circuits redrawn in simplified form. Recall that the redrawn circuit is called an equivalent circuit.

Note: There are no general formulas for the solution of series-parallel circuits because there are so many different forms of these circuits.

Note: The total current in the series-parallel circuit depends on the effective resistance of the parallel portion and on the other resistances.

Example 6.29

Problem:

Answer the following questions related to Figure 6.58.

Question 1:

Figure 6.58 shows two resistors in series (R_2 and R_3) forming one branch of a parallel circuit. The total current (I_T) flows into the parallel circuit, splitting into two branches at point A. At what point do the branch currents rejoin to form I_T?

Answer:

At point C.

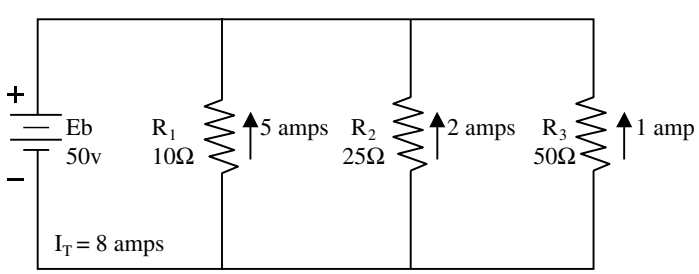

FIGURE 6.58 For Example 6.31. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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Question 2:

The source voltage E_s (30 V) is dropped between point A and point C. The largest voltage drop is across which resistor? Why?

Answer:

R_1, because the 30 V must be divided between R_2 and R_3.

Question 3:

What is the resistance of the top branch of the circuit in Figure 6.58?

Answer:

14 Ω (add R_2 and R_3).

Question 4:

What is the value of R_T?

Answer:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$= \frac{8 \times 14}{8 + 14}$$

$$= \frac{112}{22}$$

$$= 5.1\ \Omega$$

Question 5:

What is the current through the top branch ($I_{2,3}$)?

Answer:

$$I = \frac{E}{R}$$

$$= \frac{30\ \text{V}}{14\ \Omega}$$

$$= 2.14\ \text{A}$$

Question 6:

What is the value of P_T?

Answer:

$$P_T = \frac{E_S^{\ 2}}{R_T}$$

$$= \frac{30\ \text{V}^2}{5.1\ \Omega}$$

$$= 176.5\ \text{W}$$

6.20 CONDUCTORS

Earlier we mentioned that electric current moves easily through some materials, but with greater difficulty through others. Three good electrical conductors are copper, silver, and aluminum. (Generally we can say that most metals are good conductors.) Copper is the material of choice used in electrical conductors. Under special conditions, certain gases are also used as conductors (e.g., neon gas, mercury vapor, and sodium vapor are used in various kinds of lamps).

The function of the wire conductor is to connect a source of applied voltage to a load resistance with a minimum IR voltage drop in the conductor so that most of the applied voltage can produce current in the load resistance. Ideally, a conductor must have a very low resistance (e.g., a typical value for a conductor — copper — is less than 1 Ω/10 ft).

Because all electrical circuits utilize conductors of one type or another, in this Section, we discuss the basic features and electrical characteristics of the most common types of conductors. Moreover, because conductor splices and connections (and insulation of such connections) are also an essential part of any electric circuit, they are also discussed.

6.20.1 Unit Size of Conductors

A standard (or unit size) of a conductor has been established to compare the resistance and size of one conductor with another. The unit of linear measurement used is (in regards to diameter of a piece of wire) the mil (0.001 of an inch). A convenient unit of wire length used is the foot. The standard unit of size in most cases is the mil-foot (i.e., a wire will have unit size if it has diameter of 1 mil and a length of 1 ft). The resistance in ohms of a unit conductor or a given substance is called the resistivity (or specific resistance) of the substance.

As a further convenience, gauge numbers are also used in comparing the diameter of wires. The Browne and Sharpe gauge was used in the past; now the most commonly used gauge is the American wire gauge (AWG).

6.20.1.1 Square Mil

Figure 6.59 shows a square mil. The square mil is a convenient unit of cross-sectional area for square or rectangular conductors. As shown in Figure 6.59, a square mil is the area of a square, the sides of which are 1 mil. To obtain the cross-sectional area in square mils of a square conductor, square one side measured in mils. To obtain the cross-sectional area in square mils of a rectangular conductor, multiply the length of one side by that of the other, each length being expressed in mils.

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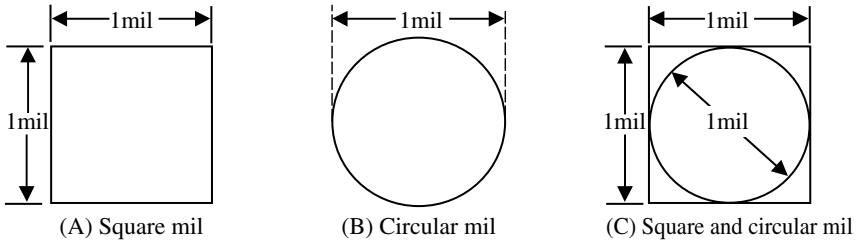

FIGURE 6.59 (A) Square mil; (B) circular mil; (C) comparison of circular to square mil. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

EXAMPLE 6.30

Problem:

Find the cross-sectional area of a large rectangular conductor 5/8 inch thick and 5 inches wide.

Solution:

The thickness may be expressed in mils as $0.625 \times 1000 = 625$ mils and the width as $5 \times 1{,}000 = 5{,}000$ mils. The cross-sectional area is $625 \times 5{,}000$, or 3,125,000 square mils.

6.20.1.2 Circular Mil

The circular mil is the standard unit of wire cross-sectional area used in most wire tables. To avoid the use of decimals (because most wires used to conduct electricity may be only a small fraction of an inch), it is convenient to express these diameters in mils. For example, the diameter of a wire is expressed as 25 mils instead of 0.025 in. A circular mil is the area of a circle having a diameter of 1 mil, as shown in Figure 6.59 (B). The area in circular mils of a round conductor is obtained by squaring the diameter measured in mils. Thus, a wire having a diameter of 25 mils has an area of 252 or 625 circular mils. By way of comparison, the basic formula for the area of a circle is:

$$A = \pi \times r^2 \tag{6.23}$$

and in this example the area in square inches is:

$$A = \pi \times r^2$$

$$= 3.14 \times 0.0125^2$$

$$= 0.00049 \text{ in.}^2$$

If D is the diameter of a wire in mils, the area in square mils can be determined using:

$$A = \Pi \times \left(\frac{D}{2}\right)^2 \tag{6.24}$$

which translates to:

$$A = \Pi \times \left(\frac{D}{2}\right)^2$$

$$= \frac{3.14}{4 \times D^2}$$

$$= 0.785\ D^2 \text{ sq. mils}$$

Thus, a wire 1 mil in diameter has an area of:

$$A = 0.785 \times 1^2$$

$$= 0.785 \text{ sq. mils}$$

which is equivalent to 1 circular mil. The cross-sectional area of a wire in circular mils is therefore determined as

$$A = \frac{0.785\ D^2}{0.785}$$

$$= D^2 \text{ circular mils}$$

where D is the diameter in mils. Therefore, the constant $\pi/4$ is eliminated from the calculation.

It should be noted that in comparing square and round conductors that the circular mil is a smaller unit of area than the square mil, and therefore there are more circular mils than square mils in any given area. The comparison is shown in Figure 6.59-C. The area of a circular mil is equal to 0.785 of a square mil.

Important Point: To determine the circular-mil area when the square-mil area is given, divide the area in square mils by 0.785. Conversely, to determine the square-mil area when the circular-mil area is given, multiply the area in circular mils by 0.785.

EXAMPLE 6.31

Problem:

A No. 12 wire has a diameter of 80.81 mils. What are (1) its area in circular mils and (2) its area in square mils?

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Solution:

Solution 1:

$$A = D^2 = 80.81^2 = 6530 \text{ circular mils}$$

Solution 2:

$$A = 0.785 \times 6530 = 5126 \text{ square mils}$$

EXAMPLE 6.32

Problem:

A rectangular conduction is 1.5 in. wide and 0.25 in. thick. What is (1) its area in square mils, and (2) what size of round conductor in circular mils is necessary to carry the same current as the rectangular bar?

Solution:

Solution 1:

$$1.5 \text{ in.} = 1.5 \times 1000 = 1{,}500 \text{ mils}$$

$$0.25 \text{ in.} = 0.25 \times 1000 = 250 \text{ mils}$$

$$A = 1500 \times 250 = 375{,}000 \text{ sq. mils}$$

Solution 2:

To carry the same current, the cross-sectional area of the rectangular bar and the cross-sectional area of the round conductor must be equal. There are more circular mils than square mils in this area, and therefore:

$$A = \frac{375{,}000}{0.785}$$

$$= 477{,}700 \text{ circular mils}$$

Note: Many electric cables are composed of stranded wires. The strands are usually single wires twisted together in sufficient numbers to make up the necessary cross-sectional area of the cable. The total area in circular mils is determined by multiplying the area of one strand in circular mils by the number of strands in the cable.

6.20.1.3 Circular-Mil-Foot

As shown in Figure 6.60, a circular-mil foot is actually a unit of volume. More specifically, it is a unit conductor 1 ft in length and having a cross-sectional area of 1 circular mil. The circular-mil-foot is useful in making comparisons between wires that are made of different metals because it is considered a unit conductor. Because it is considered a unit conductor, the circular-mil-foot is useful in making comparisons between wires that are made of different metals. For example, determining the resistance of a circular-mil-foot of each of the substances may make a basis of comparison of the resistivity of various substances.

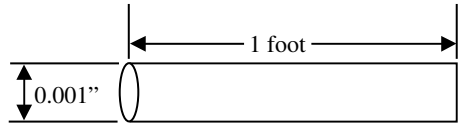

FIGURE 6.60 Circular — mil — foot. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Note: It is sometimes more convenient to employ a different unit of volume when working with certain substances. Accordingly, unit volume may also be taken as the centimeter cube. The inch cube may also be used. The unit of volume employed is given in tables of specific resistances.

6.20.1.4 Resistivity

All materials differ in their atomic structure and therefore in their ability to resist the flow of an electric current. The measure of the ability of a specific material to resist the flow of electricity is called its Resistivity, or specific resistance — the resistance in ohms offered by unit volume (the circular-mil-foot) of a substance to the flow of electric current. Resistivity is the reciprocal of conductivity (i.e., the ease by which current flows in a conductor). A substance that has a high resistivity will have a low conductivity, and vice versa.

The resistance of a given length, for any conductor, depends upon the resistivity of the material, the length of the wire, and the cross-sectional area of the wire according to the equation:

$$R = \rho \times \frac{L}{A} \tag{6.25}$$

where

R = resistance of the conductor (Ω)
L = length of the wire (ft)
A = cross-sectional area of the wire (CM)
ρ = specific resistance or resistivity (CM × Ω/ft)

The factor ρ (Greek letter rho, pronounced roe) permits different materials to be compared for resistance according to their nature without regard to different lengths or areas. Higher values of ρ mean more resistance.

Key Point: The resistivity of a substance is the resistance of a unit volume of that substance.

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TABLE 6.3
Resistivity (Specific Resistance)

Substance	Specific Resistance @ 20° (CM ft Ω)
Silver	9.8
Copper (drawn)	10.37
Gold	14.7
Aluminum	17.02
Tungsten	33.2
Brass	42.1
Steel (soft)	95.8
Nichrome	660.0

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

Many tables of resistivity are based on the resistance in ohms of a volume of the substance 1 ft long and 1 circular mil in cross-sectional area. The temperature at which the resistance measurement is made is also specified. If the kind of metal of which the conductor is made is known, the resistivity of the metal may be obtained from a table. The resistivity, or specific resistance, of some common substances is given in Table 6.3.

Note: Because silver, copper, gold, and aluminum have the lowest values of resistivity, they are the best conductors. Tungsten and iron have a much higher resistivity.

EXAMPLE 6.33

Problem:

What is the resistance of 1000 ft of copper wire having a cross-sectional area of 10,400 circular mils (No. 10 wire), the wire temperature being 20°C?

Solution:

From Table 6.3, the resistivity (specific resistance), is 10.37. Substituting the known values in the preceding Equation 6.25, the resistance R is determined as:

$$R = \rho \times \frac{L}{A}$$

$$= 10.37 \times \frac{1,000}{10,400}$$

$$= 1\ \Omega \text{ (approximately)}$$

6.20.1.5 Wire Measurement

Wires are manufactured in sizes numbered according to a table known as the AWG. Table 6.4 lists the standard wire sizes that correspond to the AWG. The gauge numbers specify the size of round wire in terms of its diameter and cross-sectional area. Note the following:

1. As the gauge numbers increase from 1 to 40, the diameter and circular area decrease. Higher gauge numbers mean smaller wire sizes. Thus, No. 12 is a smaller wire than No. 4.
2. The circular area doubles for every three-gauge size. For example, the No. 12 wire has about twice the area of the No. 15 wire.
3. The higher the gauge number and the smaller the wire, the greater the resistance of the wire for any given length. Therefore, for 1000 ft of wire, No. 12 has a resistance of 1.62 Ω, while No. 4 has a resistance of 0.253 Ω.

6.20.2 Factors Governing the Selection of Wire Size

Several factors must be considered in selecting the size of wire to be used for transmitting and distributing electric power. These factors include: allowable power loss in the line; the permissible voltage drop in the line; the current-carrying capacity of the line; and the ambient temperatures in which the wire is to be used.

1. Allowable power loss (I2R) in the line — This loss represents electrical energy converted into heat. The use of large conductors will reduce the resistance and therefore the I2R loss. However, large conductors are heavier and require more substantial supports, making them more expensive initially than small ones.
2. Permissible voltage drop (IR drop) in the line — If the source maintains a constant voltage at the input to the line, any variation in the load on the line will cause a variation in line current, and a consequent variation in the IR drop in the line. A wide variation in the IR drop in the line causes poor voltage regulation at the load.
3. The current-carrying capacity of the line — When current is drawn through the line, heat is generated. The temperature of the line will rise until the heat radiated, or otherwise dissipated, is equal to the heat generated by the passage of current through the line. If the conductor is insulated, the heat generated in the conductor is not so readily removed, as it would be if the conductor were not insulated.
4. Conductors installed where ambient temperature is relatively high — When installed in such surroundings, the heat generated by external sources constitutes an appreciable part of the total conductor heating. Due allowance must be made for the influence of external heating on the allowable conductor current and each case has its own specific limitations.

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TABLE 6.4
Copper Wire Table

Gauge #	Diameter	Circular mils	Ohms/1000 ft @ 25°C
1	289.0	83,700.0	.126
2	258.0	66,400.0	.159
3	229.0	52,600.0	.201
4	204.0	41,700.0	.253
5	182.0	33,100.0	.319
6	162.0	26,300.0	.403
7	144.0	20,800.0	.508
8	128.0	16,500.0	.641
9	114.0	13,100.0	.808
10	102.0	10,400.0	1.02
11	91.0	8,230.0	1.28
12	81.0	6,530.0	1.62
13	72.0	5,180.0	2.04
14	64.0	4,110.0	2.58
15	57.0	3,260.0	3.25
16	51.0	2,580.0	4.09
17	45.0	2,050.0	5.16
18	40.0	1,620.0	6.51
19	36.0	1,290.0	8.21
20	32.0	1,020.0	10.4
21	28.5	810.0	13.1
22	25.3	642.0	16.5
23	22.6	509.0	20.8
24	20.1	404.0	26.4
25	17.9	320.0	33.0
26	15.9	254.0	41.6
27	14.2	202.0	52.5
28	12.6	160.0	66.2
29	11.3	127.0	83.4
30	10.0	101.0	105.0
31	8.9	79.7	133.0
32	8.0	63.2	167.0
33	7.1	50.1	211.0
34	6.3	39.8	266.0
35	5.6	31.5	335.0
36	5.0	25.0	423.0
37	4.5	19.8	533.0
38	4.0	15.7	673.0
39	3.5	12.5	848.0
40	3.1	9.9	1070.0

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

6.20.2.1 Copper vs. Other Metal Conductors

If it were not cost prohibitive, silver, the best conductor of electron flow (electricity), would be the conductor of choice in electrical systems. Instead, silver is used only in special circuits where a substance with high conductivity is required.

The two most generally used conductors are copper and aluminum. Each has characteristics that make its use advantageous under certain circumstances. Likewise, each has certain disadvantages or limitations.

TABLE 6.5
Characteristics of Copper and Aluminum

Characteristics	Copper	Aluminum
Tensile strength (psi)	55,000	25,000
Tensile strength for same conductivity (lb)	55,000	40,000
Weight for same conductivity (lb)	100	48
Cross-section for same conductivity (CM)	100	160
Specific resistance (Ω/mil ft)	10.6	17

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

Copper has a higher conductivity, is more ductile (can be drawn out into wire), has relatively high tensile strength, and can be easily soldered. It is more expensive and heavier than aluminum.

Aluminum has only about 60% of the conductivity of copper, but its lightness makes possible long spans, and its relatively large diameter for a given conductivity reduces corona (i.e., the discharge of electricity from the wire when it has a high potential). The discharge is greater when smaller diameter wire is used than when larger diameter wire is used. However, aluminum conductors are not easily soldered, and aluminum's relatively large size for a given conductance does not permit the economical use of an insulation covering.

Note: Recent practice involves using copper wiring (instead of aluminum wiring) in house and some industrial applications. This is the case because aluminum connections are not as easily made as they are with copper. In addition, over the years, many fires have been started because of improperly connected aluminum wiring (i.e., poor connections equals high resistance connections, resulting in excessive heat generation).

A comparison of some of the characteristics of copper and aluminum is given in Table 6.5.

6.20.2.2 Temperature Coefficient

The resistance of pure metals, such as silver, copper, and aluminum, increases as the temperature increases. The temperature coefficient of resistance, α (Greek letter alpha), indicates how much the resistance changes for a change in temperature. A positive value for α means R increases with temperature, a negative α means R decreases, and a zero α means R is constant, not varying with changes in temperature. Typical values of α are listed in Table 6.5.

The amount of increase in the resistance of a 1-Ω sample of the copper conductor per degree rise in temperature (i.e., the temperature coefficient of resistance) is approximately 0.004. For pure metals, the temperature coefficient of resistance ranges between 0.004 and 0.006 Ω.

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TABLE 6.6
Properties of Conducting Materials

Material	Temperature Coefficient, Ω/°C
Aluminum	0.004
Carbon	–0.0003
Constantan	0 (average)
Copper	0.004
Gold	0.004
Iron	0.006
Nichrome	0.0002
Nickel	0.005
Silver	0.004
Tungsten	0.005

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

Thus, a copper wire having a resistance of 50 ohms at an initial temperature of 0°C will have an increase in resistance of 50×0.004, or 0.2 Ω (approximate), for the entire length of wire for each degree of temperature rise above 0°C. At 20°C, the increase in resistance is approximately 20×0.2, or 4 Ω. The total resistance at 20°C is 50 + 4, or 54 Ω.

Note: As shown in Table 6.6, carbon has a negative temperature coefficient. In general, α is negative for all semiconductors such as germanium and silicon. A negative value for α means less resistance at higher temperatures. Therefore, the resistance of semiconductor diodes and transistors can be reduced considerably when they become hot with normal load current. Also note that constantan has a value of zero for α (Table 6.6). Thus, it can be used for precision wire-wound resistors, which do not change resistance when the temperature increases.

6.20.3 Conductor Insulation

Electric current must be contained; it must be channeled from the power source to a useful load — safely. To accomplish this, electric current must be forced to flow only where it is needed. Moreover, current-carrying conductors must not be allowed (generally) to come in contact with one another, their supporting hardware, or personnel working near them. To accomplish this, conductors are coated or wrapped with various materials. These materials have such a high resistance that they are, for all practical purposes, nonconductors. They are generally referred to as insulators or insulating materials.

There is a wide variety of insulated conductors available to meet the requirements of any job. However, only the necessary minimum of insulation is applied for any particular type of cable designed to do a specific job. This is the case because insulation is expensive and has a stiffening effect; it is also required to meet a great variety of physical and electrical conditions.

Two fundamental, but distinctly different, properties of insulation materials (e.g., rubber, glass, asbestos, and plastics) are insulation resistance and dielectric strength.

1. Insulation resistance — The resistance to current leakage through and over the surface of insulation materials.
2. Dielectric strength — is the ability of the insulator to withstand potential difference. It is usually expressed in terms of the voltage at which the insulation fails because of the electrostatic stress.

Various types of materials are used to provide insulation for electric conductors, including rubber, plastics, varnished cloth, paper, silk and cotton and enamel.

6.20.4 Conductor Splices and Terminal Connections

When conductors join each other, or connect to a load, *splices* or *terminals* must be used. It is important that they be properly made, since any electric circuit is only as good as its weakest connection. The basic requirement of any splice or connection is that it be both mechanically and electrically as strong as the conductor or device with which it is used. High quality workmanship and materials must be employed to ensure lasting electrical contact, physical strength, and insulation (if required).

Important Point: Conductor splices and connections are an essential part of any electric circuit.

6.20.5 Soldering Operations

Soldering operations are a vital part of electrical and electronics maintenance procedures. Soldering is a manual skill that must be learned by all personnel who work in the field of electricity. Practice is required to develop proficiency in the techniques of soldering.

In performing a soldering operation, both the solder and the material to be soldered (e.g., electric wire and terminal lugs) must be heated to a temperature, which allows the solder to flow. If either is heated inadequately, cold solder joints result (i.e., high resistance connections are created). Such joints do not provide either the physical strength or the electrical conductivity required. In soldering operations it is also necessary to select a solder that will flow at a temperature low enough to avoid damage to the part being soldered, or to any other part or material in the immediate vicinity.

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6.20.6 Solderless Connections

Generally, terminal lugs and splicers, which do not require solder, are more widely used (because they are easier to mount correctly) than those that do require solder. Solderless connectors, made in a wide variety of sizes and shapes, are attached to their conductors by means of several different devices, but the principle of each is essentially the same. They are all crimped (squeezed) tightly onto their conductors. They both afford adequate electrical contact and great mechanical strength.

6.20.7 Insulation Tape

The carpenter has his saw, the dentist his pliers, the plumber his wrench, and the electrician his insulating tape. Accordingly, one of the first things the rookie maintenance operator learns (also in addition to learning proper and safe techniques for performing electrical work) is the value of electrical insulation tape. Normally, the use of electrical insulating tape comes into play as the final step in completing a splice or joint: to place insulation over the bare wire at the connection point.

Typically insulation tape used should be the same basic substance as the original insulation, usually a rubber-splicing compound. When using rubber (latex) tape as the splicing compound where the original insulation was rubber, it should be applied to the splice with a light tension so that each layer presses tightly against the one underneath it. In addition to the rubber tape application (which restores the insulation to original form), restoring with friction tape is also often necessary.

In recent years, plastic electrical tape has come into wide use. It has certain advantages over rubber and friction tape. For example, it will withstand higher voltages for a given thickness. Single thin layers of certain commercially available plastic tape will stand several thousand volts without breaking down.

Important Point: Be advised that though the use of plastic electrical tape has become almost universal in industrial applications, it must be applied in more layers. This is because it is thinner than rubber or friction tape, ensuring an extra margin of safety.

6.21 ELECTROMAGNETISM

Earlier we discussed the fundamental theories concerning simple magnets and magnetism. Those discussions dealt mainly with forms of magnetism that were not related directly to electricity (e.g., permanent magnets). Further, only brief mention was made of those forms of magnetism having direct relation to electricity — (e.g., producing electricity with magnetism).

In medicine, anatomy and physiology are so closely related that the medical student cannot study one at length without involving the other. A similar relationship holds for the electrical field — magnetism and basic electricity are so closely related that one cannot be studied at length without involving the other. This close fundamental relationship is continually borne out in subsequent sections that follow, such as in the study of generators, transformers, and motors. To be proficient in electricity, the operator must become familiar with such general relationships that exist between magnetism and electricity as follows:

1. Electric current flow will always produce some form of magnetism.
2. Magnetism is by far the most commonly used means for producing or using electricity.
3. The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

6.21.1 Magnetic Field around a Single Conductor

In 1819, Hans Christian Oersted, a Danish scientist, discovered that a field of magnetic force exists around a single wire conductor carrying an electric current. In Figure 6.61, a wire is passed through a piece of cardboard and connected through a switch to a dry cell. With the switch open (no current flowing), if we sprinkle iron filings on the cardboard then tap it gently, the filings will fall back haphazardly. If we close the switch, current will begin to flow in the wire. If we tap the cardboard again, the magnetic effect of the current in the wire will cause the filings to fall back into a definite pattern of concentric circles with the wire as the center of the circles. Every section of the wire has this field of force around it in a plane perpendicular to the wire, as shown in Figure 6.62.

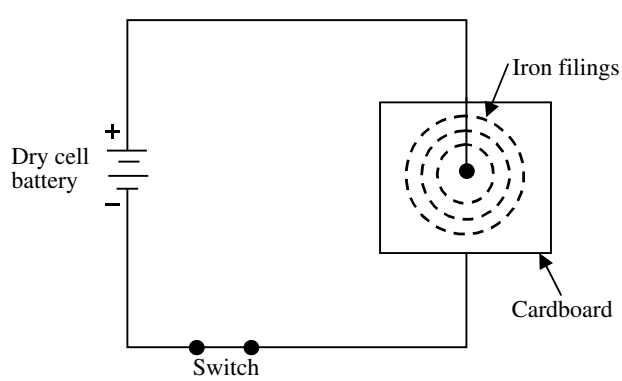

FIGURE 6.61 A circular pattern of magnetic force exists around a wire carrying an electric current. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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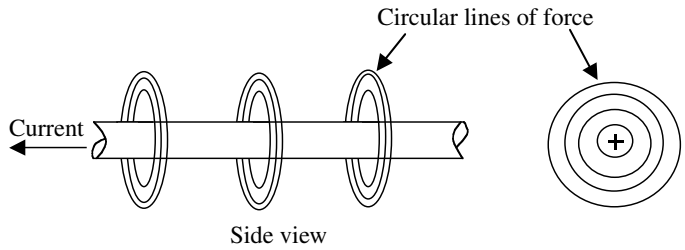

FIGURE 6.62 The circular fields of force around a wire carrying a current are in planes perpendicular to the wire. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

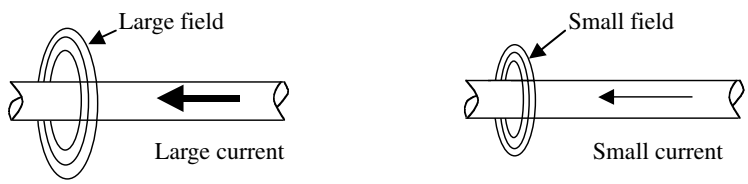

FIGURE 6.63 The strength of the magnetic field around a wire carrying current depends on the amount of current. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

The ability of the magnetic field to attract bits of iron (as demonstrated in Figure 6.61) depends on the number of lines of force present. The strength of the magnetic field around a wire carrying a current depends on the current, since it is the current that produces the field. The greater the current, the greater the strength of the field. A large current will produce many lines of force extending far from the wire, while a small current will produce only a few lines close to the wire (see Figure 6.63).

6.21.2 Polarity of a Single Conductor

The relation between the direction of the magnetic lines of force around a conductor and the direction of current flow along the conductor may be determined by means of the left-hand rule for a conductor. If the conductor is grasped in the left hand with the thumb extended in the direction of electron flow (– to +), the fingers will point in the direction of the magnetic lines of force. The north pole of a compass would point this same direction if the compass were placed in the magnetic field.

Important Note: Arrows are generally used in electric diagrams to denote the direction of current flow along the length of wire. Where cross sections of wire are shown, a special view of the arrow is used. A cross-sectional view of a conductor that is carrying current toward the observer is illustrated in Figure 6.64A. The direction of current is indicated by a dot, which represents the head of the arrow. A conductor that is carrying current away from the observer is illustrated in Figure 6.64B. A cross, which represents the tail of the arrow, indicates the direction of current.

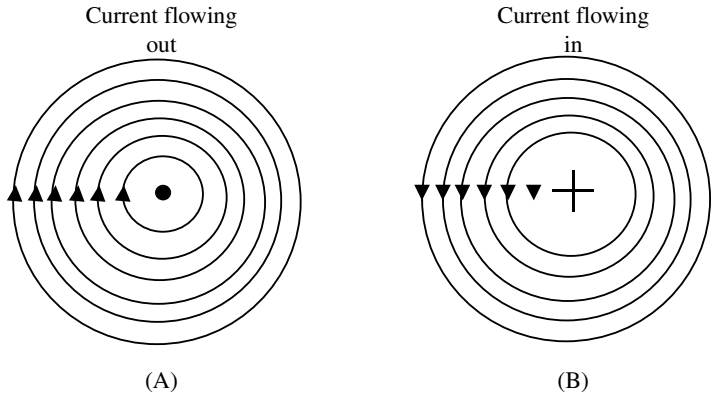

FIGURE 6.64 Magnetic field around two parallel conductors. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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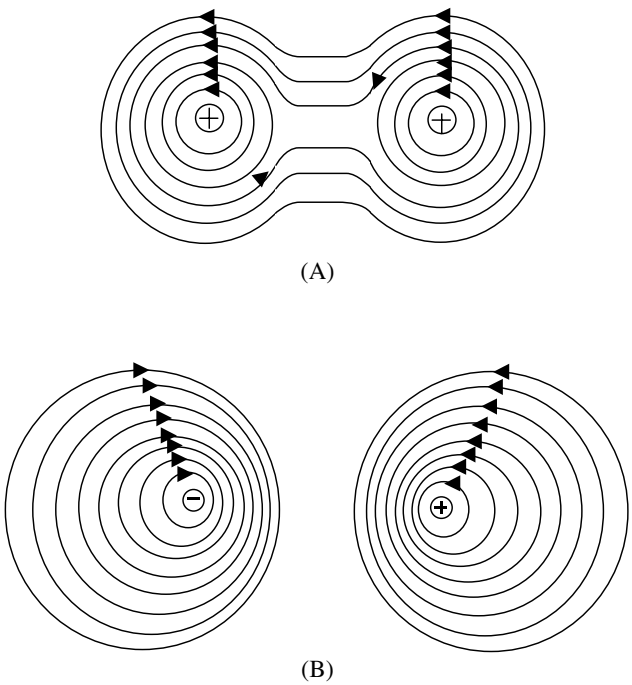

FIGURE 6.65 (A) Current flowing in the same direction; (B) current flowing in opposite directions. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.21.3 Field around Two Parallel Conductors

When two parallel conductors carry current in the same direction, the magnetic fields tend to encircle both conductors, drawing them together with a force of attraction, as shown in Figure 6.65A. Two parallel conductors carrying currents in opposite directions are shown in Figure 6.65B. The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force are crowded together in the space between the wires, and tend to push the wires apart. Therefore, two parallel adjacent conductors carrying currents in the same direction attract each other, and two parallel conductors carrying currents in opposite directions repel each other.

6.21.4 Magnetic Field of a Coil

The magnetic field around a current-carrying wire exists at all points along its length. Bending the current-carrying wire into the form of a single loop has two results. First, the magnetic field consists of more dense concentric circles in a plane perpendicular to the wire, although the total number of lines is the same as for the straight conductor. Second, all the lines inside the loop are in the same direction. When this straight wire is wound around a core, it becomes a coil and the magnetic field assumes a different shape. When current is passed through the coiled conductor, the magnetic field of each turn of wire links with the fields of adjacent turns. The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil will be a north pole and the other end will be a south pole.

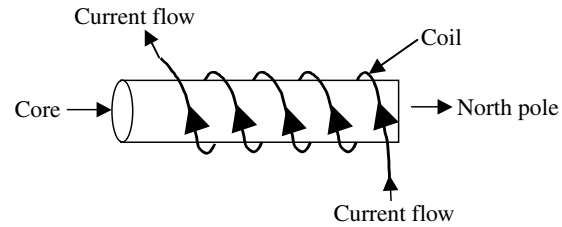

FIGURE 6.66 Current-carrying coil. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.21.4.1 Polarity of an Electromagnetic Coil

As mentioned, it was shown that the direction of the magnetic field around straight conductor depends on the direction of current flow through that conductor. A reversal of current flow through a conductor causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current flow through a coil also causes a reversal of its two-pole field. This is true because that field is the product of the linkage between the individual turns of wire on the coil. If the field of each turn is reversed, it follows that the total field (coil's field) is also reversed.

When the direction of electron flow through a coil is known, its polarity may be determined by use of the left-hand rule for coils. This rule is stated as follows: grasping the coil in the left hand, with the fingers wrapped around in the direction of electron flow, the thumb will point toward the north pole (see Figure 6.66).

6.21.4.2 Strength of an Electromagnetic Field

The strength, or intensity, of the magnetic field of a coil depends on a number of factors.

1. The number of turns of conductor.
2. The amount of current flow through the coil.
3. The ratio of the coil's length to its width.
4. The type of material in the core.

6.21.5 Magnetic Units

The law of current flow in the electric circuit is similar to the law for the establishing of flux in the magnetic circuit.

The magnetic flux, ϕ, (phi) is similar to current in the Ohm's law formula, and comprises the total number of lines of force existing in the magnetic circuit. The Maxwell is the unit of flux —1 line of force is equal to 1 Maxwell.

Note: The Maxwell is often referred to as simply a line of force, line of induction, or line.

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The strength of a magnetic field in a coil of wire depends on how much current flows in the turns of the coil. The more current, the stronger the magnetic field. In addition, the more turns, the more concentrated are the lines of force. The force that produces the flux in the magnetic circuit (comparable to electromotive force in Ohm's law) is known as Magnetomotive force (MMF). The practical unit of MMF is the ampere-turn (At). In equation form,

$$F = \text{ampere-turns} = N \times I \tag{6.26}$$

where

F = MMF (At)
N = number of turns
I = current (A)

Example 6.34

Problem:

Calculate the ampere-turns for a coil with 2000 turns and a 5-mA current.

Solution:

Use Equation 6.26 and substitute N = 2000 and I = 5×10^{-3} A.

$$H \times I = 2000 \times (5 \times 10^{-3}) = 10 \text{ At}$$

The unit of intensity of magnetizing force per unit of length is designated as H, and is sometimes expressed as Gilberts per centimeter of length. Expressed as an equation,

$$H = \frac{N \times I}{L} \tag{6.27}$$

where

H = magnetic field intensity (At/m)
NI = ampere-turns (At)
L = length between poles of the coil (m)

Note: Equation 6.27 is for a solenoid. H is the intensity of an air core. With an iron core, H is the intensity through the entire core and L is the length or distance between poles of the iron core.

6.21.6 Properties of Magnetic Materials

In this section, we discuss two important properties of magnetic materials: permeability and hysteresis.

6.21.6.1 Permeability

When the core of an electromagnet is made of annealed sheet steel, it produces a stronger magnet than if a cast iron core is used. This is because the magnetizing force of the coil more readily acts upon annealed sheet steel than is the hard cast iron. Simply put, soft sheet steel is said to have greater permeability because of the greater ease with which magnetic lines are established in it.

Recall that permeability is the relative ease with which a substance conducts magnetic lines of force. The permeability of air is arbitrarily set at one. The permeability of other substances is the ratio of their ability to conduct magnetic lines compared to that of air. The permeability of nonmagnetic materials, such as aluminum, copper, wood, and brass is essentially unity, or the same as for air.

Note: The permeability of magnetic materials varies with the degree of magnetization, being smaller for high values of flux density.

Note: Reluctance, which is analogous to resistance, is the opposition to the production of flux in a material and is inversely proportional to permeability. Iron has high permeability and therefore, low reluctance. Air has low permeability and hence high reluctance.

6.21.6.2 Hysteresis

When the current in a coil of wire reverses thousands of times per second, a considerable loss of energy can occur. This loss of energy is caused by hysteresis. Hysteresis means a lagging behind — the magnetic flux in an iron core lags behind the increases or decreases of the magnetizing force.

The simplest method of illustrating the property of hysteresis is by graphical means such as the hysteresis loop shown in Figure 6.67.

The hysteresis loop is a series of curves that show the characteristics of a magnetic material. Opposite directions of current result are in the opposite directions of +H and –H for field intensity. Similarly, opposite polarities are shown for flux density as +B and –B. The current starts

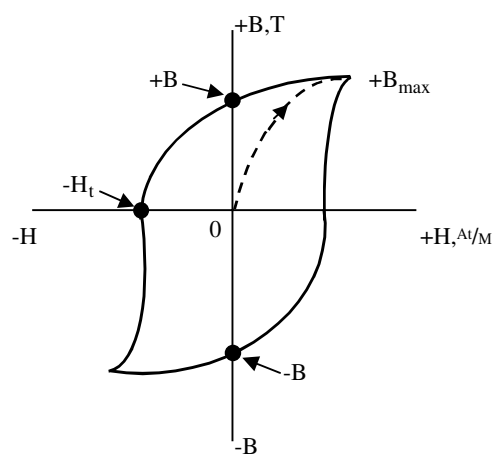

FIGURE 6.67 Hysteresis loop. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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at the center zero when the material is unmagnetized. Positive H values increase B to saturation at $+B_{max}$. Next H decreases to zero, but B drops to the value of B, because of hysteresis. The current that produced the original magnetization now is reversed so that H becomes negative. B drops to zero and continues to $-B_{max}$. As the –H values decrease, B is reduced to –B, when H is zero. With a positive swing of current, H becomes positive, producing saturation at $+B_{max}$ again. The hysteresis loop is now completed. The curve does not return to zero at the center because of hysteresis.

6.21.7 Electromagnets

An electromagnet is composed of a coil of wire wound around a core that is normally soft iron due to its high permeability and low hysteresis. When direct current flows through the coil, the core will become magnetized with the same polarity that the coil would have without the core. If the current is reversed, the polarity of the coil and core are reversed.

The electromagnet is of great importance in electricity simply because the magnetism can be turned on or turned off at will. The starter solenoid (an electromagnet) in automobiles and powerboats is a good example. In an automobile or boat, an electromagnet is part of a relay that connects the battery to the induction coil, generating the very high voltage needed to start the engine. The starter solenoid isolates this high voltage from the ignition switch. When no current flows in the coil, it is an air core, but when the coil is energized, a movable soft-iron core does two things. First, the magnetic flux is increased because the soft-iron core is more permeable than the air core. Second, the flux is more highly concentrated. All this concentration of magnetic lines of force in the soft-iron core results in a very good magnet when current flows in the coil. However, soft iron loses its magnetism quickly when the current is shut off. The effect of the soft iron is the same whether it is movable, as in some solenoids, or permanently installed in the coil. An electromagnet then consists of a coil and a core; it becomes a magnet when current flows through the coil.

The ability to control the action of magnetic force makes an electromagnet very useful in many circuit applications.

6.22 AC THEORY

Because voltage is induced in a conductor when lines of force are cut, the amount of the induced emf depends on the number of lines cut in a unit time. To induce an EMF of 1 V, a conductor must cut 100,000,000 lines of force/sec. To obtain this great number of cuttings, the conductor is formed into a loop and rotated on an axis at great speed (see Figure 6.68). The two sides of the loop become individual conductors in series, each side of the loop cutting lines of force and inducing twice the voltage that a single conductor would induce. In commercial

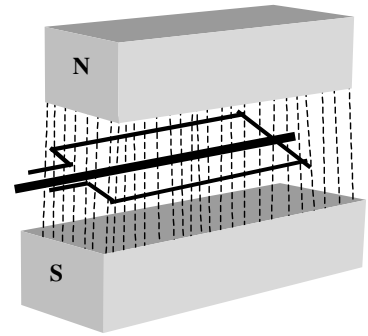

FIGURE 6.68 Loop rotating in a magnetic field produces an AC voltage. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

generators, the number of "cuttings" and the resulting emf are increased by:

1. Increasing the number of lines of force by using more magnets or stronger electromagnets,
2. Using more conductors or loops
3. Rotating the loops faster

How an AC generator operates to produce an AC voltage and current is a basic concept today, taught in elementary and middle school science classes. Today we accept technological advances as commonplace; we surf the Internet, watch cable television, use our cell phones, and take space flight as a given. We consider producing the electricity that makes all these technologies possible as our right. These technologies are bottom shelf to us today — we have them available to us so we simply use them. This point of view was surely not held initially, especially by those who broke ground in developing technology and electricity.

In the groundbreaking years of electric technology development, the geniuses of the science of electricity (including George Simon Ohm) performed their technological breakthroughs in faltering steps. We tend to forget that those first faltering steps of scientific achievement in the field of electricity were performed with crude, and for the most part, homemade apparatus.

The innovators of electricity had to fabricate nearly all the laboratory equipment used in their experiments. At the time, the only convenient source of electrical energy available to these early scientists was the voltaic cell, invented some years earlier. Because of the fact that cells and batteries were the only sources of power available, some of the early electrical devices were designed to operate from direct current.

Initially, direct current was used extensively. When the use of electricity became widespread, certain disadvantages in the use of direct current became apparent. In a DC system, the supply voltage must be generated at the level required by the load. To operate a 240-V lamp for example,

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the generator must deliver 240 V. A 120-V lamp could not be operated from this generator by any convenient means. A resistor could be placed in series with the 120-V lamp to drop the extra 120 V, but the resistor would waste an amount of power equal to that consumed by the lamp.

Another disadvantage of DC systems is the large amount of power lost due to the resistance of the transmission wires used to carry current from the generating station to the consumer. This loss could be greatly reduced by operating the transmission line at very high voltage and low current. This is not a practical solution in a DC system, since the load would also have to operate at high voltage. Because of the difficulties encountered with direct current, practically all modern power distribution systems use alternating current AC, including water and wastewater treatment plants.

Unlike DC voltage, AC voltage can be stepped up or down by a device called a transformer. Transformers permit the transmission lines to be operated at high voltage and low current for maximum efficiency. Then at the consumer end the voltage is stepped down to whatever value the load requires by using a transformer. Due to its inherent advantages and versatility, alternating current has replaced direct current in all but a few commercial power distribution systems.

6.22.1 Basic AC Generator

As shown in Figure 6.68, an AC voltage and current can be produced when a conductor loop rotates through a magnetic field and cuts lines of force to generate an induced AC voltage across its terminals. This describes the basic principle of operation of an alternating current generator, or alternator. An alternator converts mechanical energy into electrical energy. It does this by utilizing the principle of electromagnetic induction. The basic components of an alternator are an armature, about which many turns of conductor are wound, which rotates in a magnetic field, and some means of delivering the resulting alternating current to an external circuit.

6.22.1.1 Cycle

An AC voltage is one that continually changes in magnitude and periodically reverses in polarity (see Figure 6.69). The zero axis is a horizontal line across the center. The vertical variations on the voltage wave show the changes in magnitude. The voltages above the horizontal axis have positive (+) polarity, while voltages below the horizontal axis have negative (–) polarity.

Figure 6.70 shows a suspended loop of wire (conductor or armature) being rotated (moved) in a counterclockwise direction through the magnetic field between the poles of a permanent magnet. For ease of explanation, the loop has been divided into a thick and thin half. Notice that in part

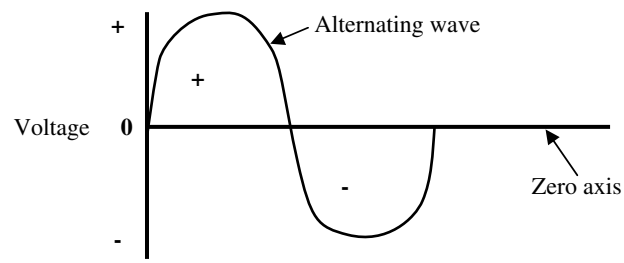

FIGURE 6.69 An AC voltage waveform. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

A, the thick half is moving along (parallel to) the lines of force. Consequently, it is cutting none of these lines. The same is true of the thin half that is moving in the opposite direction. Because the conductors are not cutting any lines of force, no EMF is induced. As the loop rotates toward the position shown in part B, it cuts more and more lines of force per second because it is cutting more directly across the field (lines of force) as it approaches the position shown in B. At position B, the induced voltage is greatest because the conductor is cutting directly across the field.

As the loop continues to be rotated toward the position shown in part C, it cuts fewer and fewer lines of force per second. The induced voltage decreases from its peak value. Eventually, the loop is once again moving in a plane parallel to the magnetic field, and no voltage (zero voltage) is induced. The loop has now been rotated through half a circle (one alternation, or 180°). The sine curve shown in the lower part of Figure 6.70 shows the induced voltage at every instant of rotation of the loop. Notice that this curve contains 360°, or two alternations. Two alternations represent one complete circle of rotation.

Important Point: Two complete alternations in a period is called a cycle.

In Figure 6.70, if the loop is rotated at a steady rate, and if the strength of the magnetic field is uniform, the number of cycles per second (cps), or hertz, and the voltage will remain at fixed values. Continuous rotation will produce a series of sine-wave voltage cycles, or, in other words, an AC voltage. In this way, mechanical energy is converted into electrical energy.

6.22.1.2 Frequency, Period, and Wavelength

The frequency of an alternating voltage or current is the number of complete cycles occurring in each second of time. It is indicated by the symbol f and is expressed in hertz (Hz). A measurement of 1 cps equals 1 Hz. Thus, 60 cps equals 60 Hz. A frequency of 2 Hz (Figure 6.71A) is twice the frequency of 1 Hz (Figure 6.71B).

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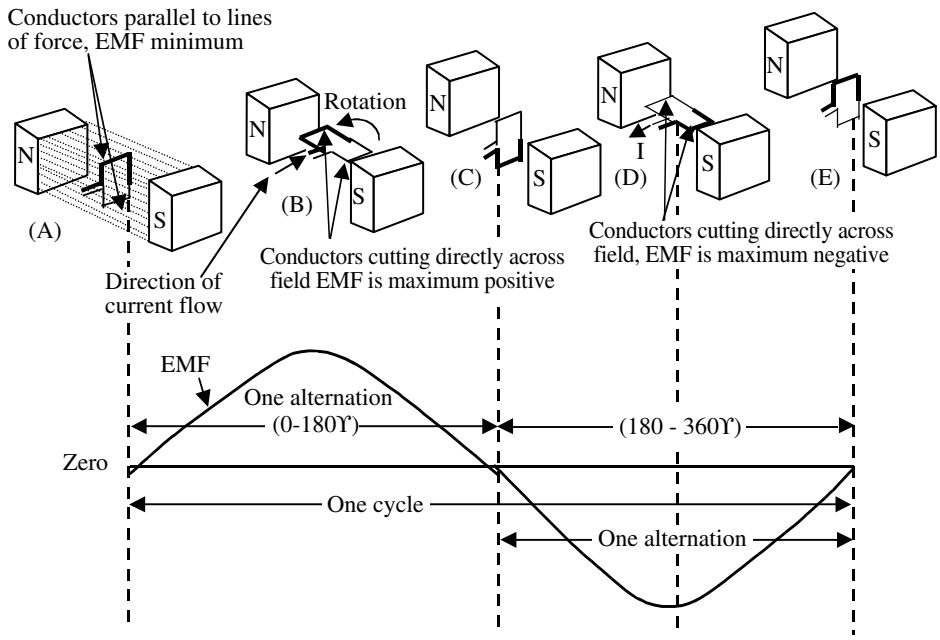

FIGURE 6.70 Basic alternating-current generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

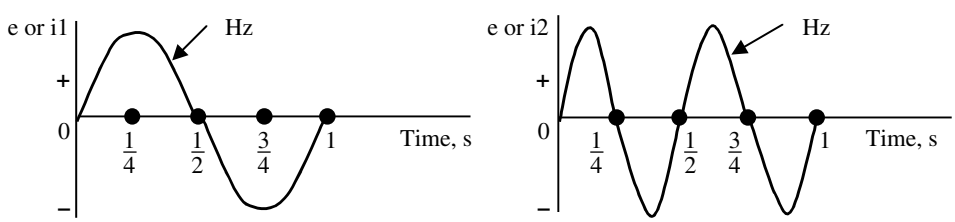

FIGURE 6.71 Comparison of frequencies. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

The amount of time for the completion of 1 cycle is the period. It is indicated by the symbol T for time and is expressed in seconds. Frequency and period are reciprocals of each other:

$$f = \frac{1}{T} \tag{6.28}$$

$$T = \frac{1}{f} \tag{6.29}$$

Important Point: The higher the frequency, the shorter the period.

The angle of 360° represents the time for 1 cycle, or the period T. Therefore, we can show the horizontal axis of the sine wave in units of either electrical degrees or seconds (see Figure 6.72).

The wavelength is the length of one complete wave or cycle. It depends upon the frequency of the periodic variation and its velocity of transmission. It is indicated by the symbol λ (Greek lowercase lambda). Expressed as a formula:

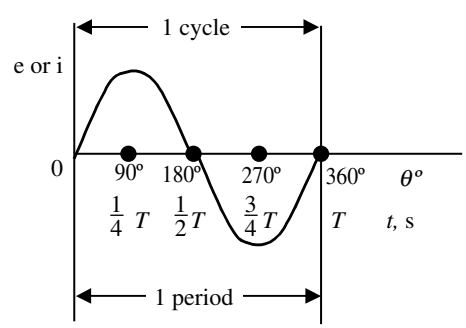

FIGURE 6.72 Relationship between electrical degrees and time. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

$$\lambda = \frac{\text{Velocity}}{\text{Frequency}} \tag{6.30}$$

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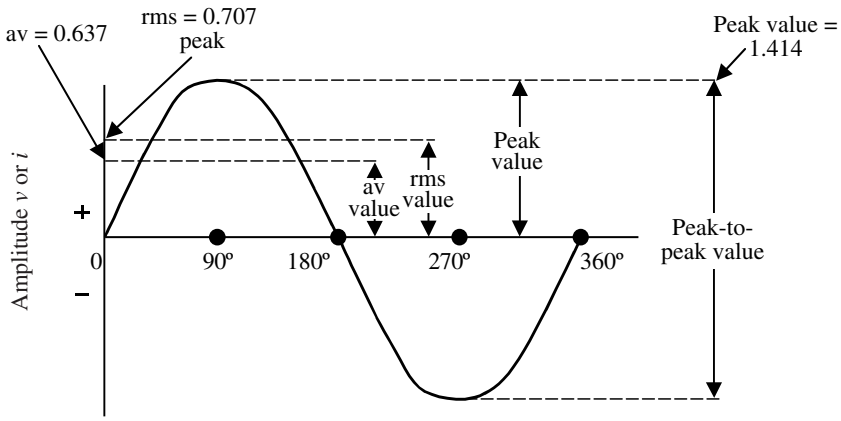

FIGURE 6.73 Amplitude values for AC sine wave. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.22.2 Characteristic Values of AC Voltage and Current

Because an AC sine wave voltage or current has many instantaneous values throughout the cycle, it is convenient to specify magnitudes for comparing one wave with another. The peak, average, or root-mean-square (rms) value can be specified (see Figure 6.73). These values apply to current or voltage.

6.22.2.1 Peak Amplitude

One of the most frequently measured characteristics of a sine wave is its amplitude. Unlike DC measurement, the amount of alternating current or voltage present in a circuit can be measured in various ways. In one method of measurement, the maximum amplitude of either the positive or the negative alternation is measured. The value of current or voltage obtained is called the peak voltage or the peak current. To measure the peak value of current or voltage, an oscilloscope must be used. The peak value is illustrated in Figure 6.73.

6.22.2.2 Peak-to-Peak Amplitude

A second method of indicating the amplitude of a sine wave consists of determining the total voltage or current between the positive and negative peaks. This value of current or voltage is called the *peak-to-peak value* (see Figure 6.73). Because both alternations of a pure sine wave are identical, the peak-to-peak value is twice the peak value. Peak-to-peak voltage is usually measured with an oscilloscope, although some voltmeters have a special scale calibrated in peak-to-peak volts.

6.22.2.3 Instantaneous Amplitude

The instantaneous value of a sine wave of voltage for any angle of rotation is expressed by the formula:

$$e = E_m \times \sin\theta \tag{6.31}$$

where

e = the instantaneous voltage
E_m = the maximum or peak voltage
$\sin\theta$ = the sine of angle at which e is desired.

Similarly the equation for the instantaneous value of a sine wave of current would be:

$$i = I_m \times \sin\theta \tag{6.32}$$

where

i = the instantaneous current
I_m = the maximum or peak current
$\sin\theta$ = the sine of the angle at which i is desired

Note: The instantaneous value of voltage constantly changes as the armature of an alternator moves through a complete rotation. Because current varies directly with voltage, according to Ohm's law, the instantaneous changes in current also result in a sine wave whose positive and negative peaks and intermediate values can be plotted exactly as we plotted the voltage sine wave. However, instantaneous values are not useful in solving most AC problems, so an effective value is used.

6.22.2.4 Effective or Root-Mean-Square Value

The effective value of an AC voltage or current of sine waveform is defined in terms of an equivalent heating effect of a direct current. Heating effect is independent of the direction of current flow.

Important Point: Since all instantaneous values of induced voltage are somewhere between zero and E_M (maximum, or peak voltage), the effective

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value of a sine wave voltage or current must be greater than zero and less than E_M (the maximum, or peak voltage).

The AC of sine waveform having a maximum value of 14.14 A produces the same amount of heat in a circuit having a resistance of 1 Ω as a direct current of 10 A. Because this is true, we can work out a constant value for converting any peak value to a corresponding effective value. The letter x represents this constant in the simple equation below. Solve for x to three decimal places.

$$14.14x = 10$$

$$x = 0.707$$

The effective value is also called the rms value because it is the square root of the average of the squared values between zero and maximum. The effective value of an AC current is stated in terms of an equivalent DC current. The phenomenon used as the standard comparison is the heating effect of the current.

Important Point: Anytime an AC voltage or current is stated without any qualifications, it is assumed an effective value.

In many instances, it is necessary to convert from effective to peak or vice-versa using a standard equation. Figure 6.73 shows that the peak value of a sine wave is 1.414 times the effective value; therefore the equation we use is:

$$E_m = E \times 1.414 \tag{6.33}$$

where

E_m = maximum or peak voltage
E = effective or rms voltage

We also use the equation:

$$I_m = I \times 1.414 \tag{6.34}$$

where

I_m = maximum or peak current
I = effective or rms current

Upon occasion, it is necessary to convert a peak value of current or voltage to an effective value. This is accomplished by using the following equations:

$$E = E_m \times 0.707 \tag{6.35}$$

where

E = effective voltage
E_m = the maximum or peak voltage

$$I = I_m \times 0.707 \tag{6.36}$$

where

I = the effective current
I_m = the maximum or peak current

6.22.2.5 Average Value

Because the positive alternation is identical to the negative alternation, the *average value* of a complete cycle of a sine wave is zero. In certain types of circuits however, it is necessary to compute the average value of one alternation. Figure 6.73 shows that the average value of a sine wave is 0.637 multiplied by peak value and therefore:

$$\text{Average Value} = 0.637 \times \text{Peak Value} \tag{6.37}$$

or

$$E_{avg} = E_m \times 0.637$$

where

E_{avg} = the average voltage of one alternation
E_m = the maximum or peak voltage

similarly

$$I_{avg} = I_m \times 0.637 \tag{6.38}$$

where

I_{avg} = the average current in one alternation
I_m = the maximum or peak current

Table 6.7 lists the various values of sine wave amplitude used to multiply in the conversion of AC sine wave voltage and current.

TABLE 6.7
AC Sine Wave Conversion Table

Multiply the Value	By	To Get the Value
Peak	2	Peak-to-peak
Peak-to-peak	0.5	Peak
Peak	0.637	Average
Average	1.637	Peak
Peak	0.707	rms (effective)
rms (effective)	1.414	Peak
Average	1.110	rms (effective)
rms (effective)	0.901	Average

Source: From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.

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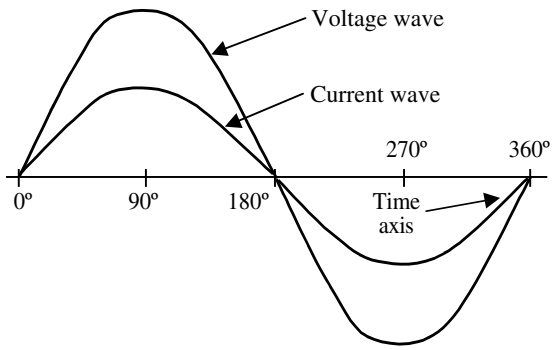

FIGURE 6.74 Voltage and current waves in phase. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.22.3 Resistance in AC Circuits

If a sine wave of voltage is applied to a resistance, the resulting current will also be a sine wave. This follows Ohm's law that states that the current is directly proportional to the applied voltage. Figure 6.74 shows a sine wave of voltage and the resulting sine wave of current superimposed on the same time axis. Notice that as the voltage increases in a positive direction, the current increases along with it. When the voltage reverses direction, the current reverses direction. At all times the voltage and current pass through the same relative parts of their respective cycles at the same time. When two waves, such as those shown in Figure 6.74, are precisely in step with one another, they are said to be in phase. To be in phase, the two waves must go through their maximum and minimum points at the same time and in the same direction.

In some circuits, several sine waves can be in phase with each other. It is possible to have two or more voltage drops in phase with each other and in phase with the circuit current.

Note: It is important to remember that Ohm's law for DC circuits are applicable to AC circuits with resistance only.

Voltage waves are not always in phase. For example, Figure 6.75 shows a voltage wave, E_1, considered to start at 0° (time 1). As voltage wave, E_1 reaches its positive peak, a second voltage wave, E_2, starts to rise (time 2). Because these waves do not go through their maximum and minimum points at the same instant of time, a phase difference exists between the two waves. The two waves are said to be out of phase. For the two waves in Figure 6.75, this phase difference is 90°.

6.22.4 Phase Relationships

In the preceding section, we discussed the important concepts of in phase and phase difference. Another important phase concept is phase angle. The phase angle between

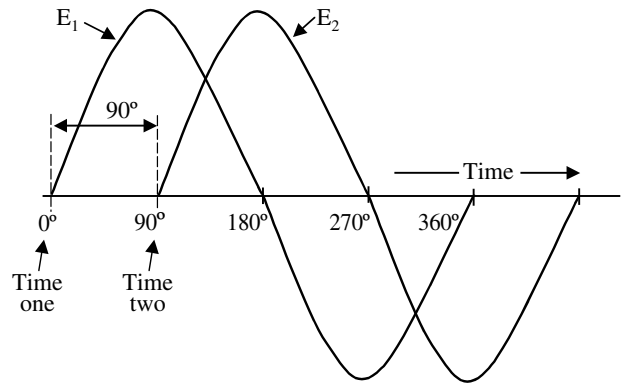

FIGURE 6.75 Voltage waves 90° out of phase. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

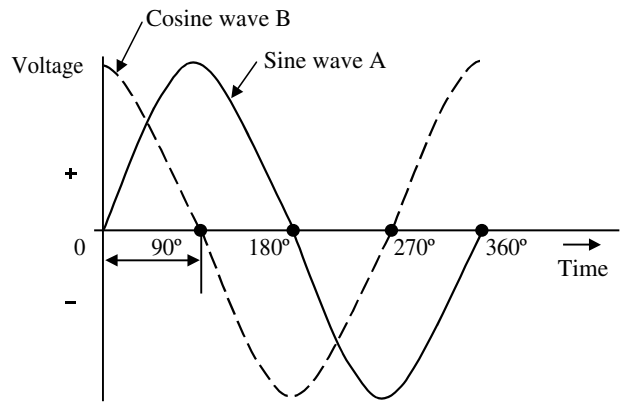

FIGURE 6.76 Wave B leads wave A by a phase angle of 90°. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

two waveforms of the same frequency is the angular difference at a given instant of time. As an example, the phase angle between waves B and A (see Figure 6.76) is 90°. Take the instant of time at 90°. The horizontal axis is shown in angular units of time. Wave B starts at maximum value and reduces to zero value at 90°, while wave A starts at zero and increases to maximum value at 90°. Wave B reaches its maximum value 90° ahead of wave A, so wave B leads wave A by 90° (and wave A lags wave B by 90°). This 90° phase angle between wave B and wave A is maintained throughout the complete cycle and all successive cycles. At any instant of time, wave B has the value that wave A will have 90° later. Wave B is a cosine wave because it is displaced 90° from wave A, which is a sine wave.

Important Point: The amount by which one wave leads or lags another is measured in degrees.

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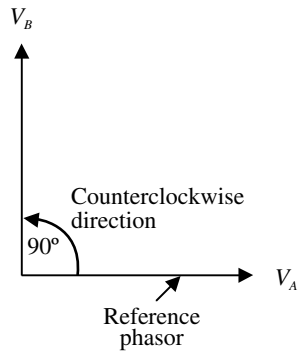

FIGURE 6.77 Phasor diagram. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

To compare phase angles or phases of alternating voltages or currents, it is more convenient to use vector diagrams corresponding to the voltage and current waveforms. A *vector* is a straight line used to denote the magnitude and direction of a given quantity. The length of the line drawn to scale denotes magnitude; the direction is indicated by the arrow at one end of the line, together with the angle that the vector makes with a horizontal reference vector.

Note: In electricity, since different directions really represent time expressed as a phase relationship, an electrical vector is called a phasor. In an AC circuit containing only resistance, the voltage and current occur at the same time, or are in phase. To indicate this condition by means of phasors, all that is necessary is to draw the phasors for the voltage and current in the same direction. The length of the phasor indicates the value of each.

A vector, or phasor, diagram is shown in Figure 6.77 where vector V_B is vertical to show the phase angle of 90° with respect to vector V_A, which is the reference. Because lead angles are shown in the counterclockwise direction from the reference vector, V_B leads V_A by 90°.

6.23 INDUCTANCE

To this point, we have learned the following key points about magnetic fields:

1. A field of force exists around a wire carrying a current.
2. This field has the form of concentric circles around the wire, in planes perpendicular to the wire, and with the wire at the center of the circles.
3. The strength of the field depends on the current. Large currents produce large fields; small currents produce small fields.
4. When lines of force cut across a conductor, a voltage is induced in the conductor.

We have also studied circuits that have been resistive (i.e., resistors presented the only opposition to current flow). Two other phenomena — inductance and capacitance — exist in DC circuits to some extent, but they are major players in AC circuits. Both inductance and capacitance present a kind of opposition to current flow that is called reactance. (Note: Other than this brief introduction to capacitance and reactance, we do not discuss these two electrical properties in detail in this text. Instead, our focus is the basics; we cover only those electrical properties important to water and wastewater operators).

Inductance is the characteristic of an electrical circuit that makes itself evident by opposing the starting, stopping, or changing of current flow. A simple analogy can be used to explain inductance. We are all familiar with how difficult it is to push a heavy load (a cart full of heavy materials, etc.). It takes more work to start the load moving than it does to keep it moving. This is because the load possesses the property of inertia. Inertia is the characteristic of mass that opposes a change in velocity. Therefore, inertia can hinder us in some ways and help us in others. Inductance exhibits the same effect on current in an electric circuit as inertia does on velocity of a mechanical object. The effects of inductance are sometimes desirable and sometimes undesirable.

Important Point: Simply put, inductance is the characteristic of an electrical conductor that opposes a change in current flow.

This means that because inductance is the property of an electric circuit that opposes any change in the current through that circuit, if the current increases, a self-induced voltage opposes this change and delays the increase. On the other hand, if the current decreases, a self-induced voltage tends to aid (or prolong) the current flow, delaying the decrease. Current can neither increase nor decrease as fast in an inductive circuit as it can in a purely resistive circuit.

In AC circuits, this effect becomes very important because it affects the phase relationships between voltage and current. Earlier we learned that voltages (or currents) could be out of phase if they are induced in separate armatures of an alternator. In that case, the voltage and current generated by each armature were in phase. When inductance is a factor in a circuit, the voltage and current generated by the same armature are out of phase. We shall examine these phase relationships later in this manual. Our objective in this chapter is to understand the nature and effects of inductance in an electric circuit.

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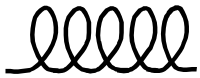

FIGURE 6.78 Schematic symbol for an inductor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

The unit for measuring inductance, L, is the henry (named for the American physicist, Joseph Henry). It is abbreviated H and normally spelled out in lower case (henry). Figure 6.78 shows the schematic symbol for an inductor. An inductor has an inductance of 1 H if an EMF of 1 V is induced in the inductor when the current through the inductor is changing at the rate of 1 ampere per second. The relation between the induced voltage, inductance, and rate of change of current with respect to time is stated mathematically as

$$E = L \times \frac{\Delta I}{\Delta t} \tag{6.39}$$

where

E = the induced emf (V)
L = the inductance (H)
ΔI = is the change (A) occurring in Δt seconds

Note: The symbol Δ (Delta) means "a change in…".

The henry is a large unit of inductance and is used with relatively large inductors. The unit employed with small inductors is the millihenry (mH). For still smaller inductors the unit of inductance is the microhenry (μH).

6.23.1 Self-Inductance

As previously explained, current flow in a conductor always produces a magnetic field surrounding, or linking with, the conductor. When the current changes, the magnetic field changes, and an EMF is induced in the conductor. This EMF is called a self-induced EMF because it is induced in the conductor carrying the current.

Note: Even a perfectly straight length of conductor has some inductance.

The direction of the induced EMF has a definite relation to the direction in which the field that induces the EMF varies. When the current in a circuit is increasing, the flux linking with the circuit is increasing. This flux cuts across the conductor and induces an EMF in the conductor in such a direction to oppose the increase in current and flux. This EMF is sometimes referred to as counterelectromotive force (cEMF). The two terms are used synonymously throughout this manual. Likewise, when the current is decreasing, an EMF is induced in the opposite direction and opposes the decrease in current.

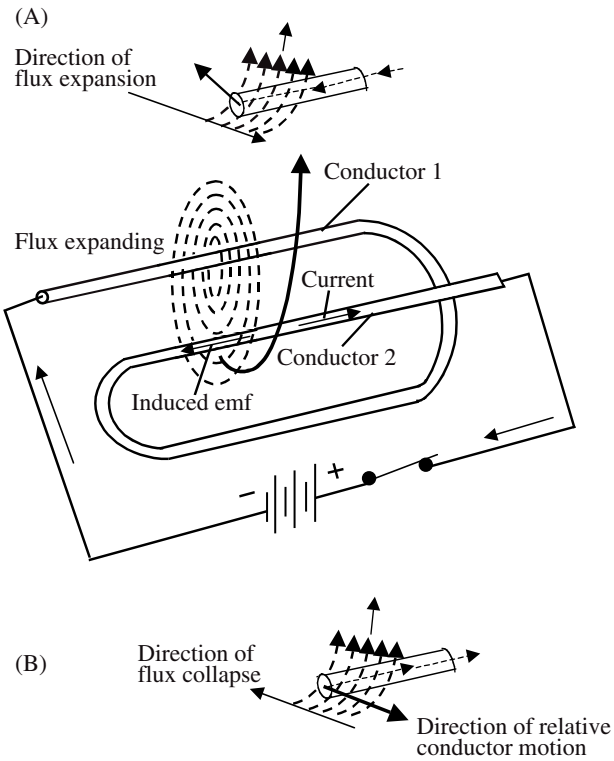

FIGURE 6.79 Self-inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Important Point: The effects just described are summarized by Lenz's law, which states that the induced emf in any circuit is always in a direction opposed to the effect that produced it.

Shaping a conductor so that the electromagnetic field around each portion of the conductor cuts across some other portion of the same conductor increases the inductance. This is shown in its simplest form in Figure 6.79A. A loop of conductor is looped so that two portions of the conductor lie adjacent and parallel to one another. These portions are labeled conductor 1 and conductor 2. When the switch is closed, electron flow through the conductor establishes a typical concentric field around all portions of the conductor. The field is shown in a single plane (for simplicity) that is perpendicular to both conductors. Although the field originates simultaneously in both conductors it is considered as originating in conductor 1 and its effect on conductor 2 will be noted. With increasing current, the field expands outward, cutting across a portion of conductor 2. The dashed arrow shows the resultant induced EMF in conductor 2. Note that it is in opposition to the battery current and voltage, according to Lenz's law.

In Figure 6.79B, the same section of conductor 2 is shown, but with the switch opened and the flux collapsing.

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FIGURE 6.80 (A) Few turns, low inductance; (B) more turns, higher inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

FIGURE 6.81 (A) Wide spacing between turns, low inductance; (B) close spacing between turns, higher inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

Important Point: From Figure 6.79, the important point to note is that the voltage of self-induction opposes both **changes** in current. It delays the initial buildup of current by opposing the battery voltage. It also delays the breakdown of current by exerting an induced voltage in the same direction that the battery voltage acted.

Four major factors affect the self-inductance of a conductor, or circuit.

1. Number of turns — Inductance depends on the number of wire turns. Wind more turns to increase inductance. Take turns off to decrease the inductance. Figure 6.80 compares the inductance of two coils made with different numbers of turns.
2. Spacing between turns — Inductance depends on the spacing between turns, or the inductor's length. Figure 6.81 shows two inductors with the same number of turns. The first inductor's turns have a wide spacing. The second inductor's turns are close together. The second coil, though shorter, has a larger inductance value because of its close spacing between turns.

FIGURE 6.82 (A) Small diameter, low inductance; (B) larger diameter, higher inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

3. Coil diameter — Coil diameter, or cross-sectional area, is highlighted in Figure 6.82. The larger-diameter inductor has more inductance. Both coils shown have the same number of turns, and the spacing between turns is the same. The first inductor has a small diameter and the second one has a larger diameter. The second inductor has more inductance than the first one.
4. Type of core material — Permeability, as pointed out earlier, is a measure of how easily a magnetic field goes through a material. Permeability also tells us how much stronger the magnetic field will be with the material inside the coil.

Figure 6.83 shows three identical coils. One has an air core, one has a powdered-iron core in the center, and the other has a soft iron core. This figure illustrates the effects of core material on inductance. The inductance of a coil is affected by the magnitude of current when the core is a magnetic material. When the core is air, the inductance is independent of the current.

Key Point: The inductance of a coil increases very rapidly as the number of turns is increased. It also increases as the coil is made shorter, the cross-sectional area is made larger, or the permeability of the core is increased.

6.23.2 Mutual Inductance

When the current in a conductor or coil changes, the varying flux can cut across any other conductor or coil located nearby, thus inducing voltages in both. A varying current in L_1, therefore, induces voltage across L_1 and across L_2 (see Figure 6.84 and see Figure 6.85 for the schematic symbol for two coils with mutual inductance).

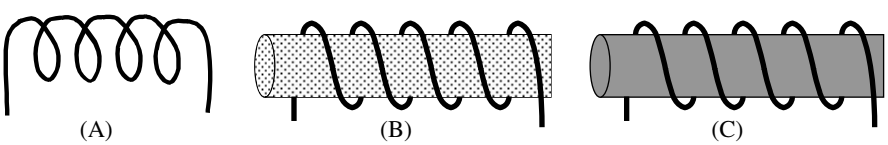

FIGURE 6.83 (A) Air core, low inductance; (B) powdered iron core, higher inductance; (C) soft iron core, highest inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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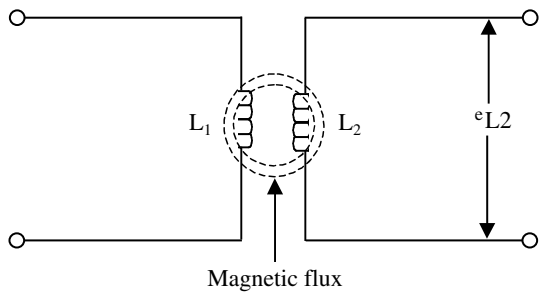

FIGURE 6.84 Mutual inductance between L_1 and L_2. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

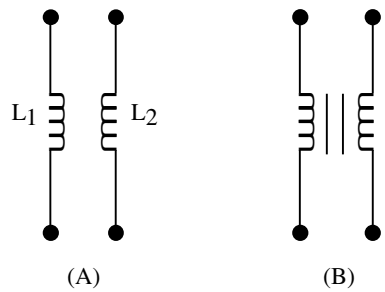

FIGURE 6.85 (A) Schematic symbol for two coils (air core) with mutual inductance; (B) two coils (iron core) with mutual inductance. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

When the induced voltage, e_{L2}, produces current in L_2, its varying magnetic field induces voltage in L_1. Hence, the two coils, L_1 and L_2, have mutual inductance because current change in one coil can induce voltage in the other. The unit of mutual inductance is the henry, and the symbol is L_M. Two coils have L_M of 1 H when a current change of 1 A/sec in one coil induces 1 E in the other coil.

The factors affecting the mutual inductance of two adjacent coils is dependent upon:

1. Physical dimensions of the two coils
2. Number of turns in each coil
3. Distance between the two coils
4. Relative positions of the axes of the two coils
5. The permeability of the cores

Important Point: The amount of mutual inductance depends on the relative position of the two coils. If the coils are separated a considerable distance, the amount of flux common to both coils is small and the mutual inductance is low. Conversely, if the coils are close together so that nearly all the flow of one coil links the turns of the other, mutual inductance is high. The mutual inductance can be increased greatly by mounting the coils on a common iron core.

6.23.3 Calculation of Total Inductance

Note: In the study of advanced electrical theory, it is necessary to know the effect of mutual inductance in solving for total inductance in both series and parallel circuits. For our purposes, in this manual we do not attempt to make these calculations. Instead, we discuss the basic total inductance calculations that the maintenance operator should be familiar with.

If inductors in series are located far enough apart, or well shielded to make the effects of mutual inductance negligible, the total inductance is calculated in the same manner as for resistances in series; we merely add them:

$$L_T = L_1 + L_2 + L_3 \ldots L_n \tag{6.40}$$

Example 6.35

Problem:

If a series circuit contains three inductors whose values are 40 μH, 50 μH, and 20 μH, what is the total inductance?

Solution:

$$L_T = 40\ \mu h + 50\ \mu h + 20\ \mu$$

$$= 110\ \mu h$$

In a parallel circuit containing inductors (without mutual inductance), the total inductance is calculated in the same manner as for resistances in parallel:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots \frac{1}{L_N} \tag{6.41}$$

Example 6.36

Problem:

A circuit contains three totally shielded inductors in parallel. The values of the three inductances are: 4 mH, 5 mH, and 10 mH. What is the total inductance?

Solution:

$$\frac{1}{L_T} = \frac{1}{4} + \frac{1}{5} + \frac{1}{10}$$

$$= 0.25 + 0.2 + 0.1$$

$$= 0.55$$

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$$L_T = \frac{1}{0.55}$$

$$= 1.8 \text{ mH}$$

6.24 PRACTICAL ELECTRICAL APPLICATIONS

As mentioned, water and wastewater operators normally have little difficulty recognizing electrical equipment within their plant site. This is the case because there are few places within the plant site (i.e., in the majority of plant sites) that an operator can go where electricity is not performing some important function. Simply stated, whether the important function be powering lighting, heating, air conditioning, pump motors, mechanized bar screens, control systems, communications equipment, or computerized systems, it would be difficult for the modern operator to imagine plant operations without the use of electrical power.

To this point in the manual, we have concentrated (in brief fashion) on the fundamentals of electricity and electric circuits. This was our goal. Along with satisfying our goal, we also understand that having a basic knowledge of electrical theory is a great accomplishment. However, knowledge of basic theory (of any type) that is not put to practical use is analogous to understanding the operation of an internal combustion engine without ever having the opportunity to work on one.

In short, for water and wastewater operators, having an understanding of basic electrical fundamentals helps to successfully pass various certification examinations — an important career enhancing achievement. Certification is, however, just one critical element (one important step) required of operators. Operators must also be qualified to operate the plant and its associated machinery, much of which is electrical equipment. To this end, we have incorporated (along with the required theory) pertinent information on electrical applications most important to operator in their daily task of operating plant electrical equipment as is was intended to be operated as it should be operated —with understanding.

6.24.1 Electrical Power Generation

Most water and wastewater treatment plants do not generate their own plant general service electrical power. Instead, and as with most other industrial users, treatment plants typically purchase electrical power from a local electrical utility company, and any on-site generation is provided only for standby power. Additionally, in smaller communities, it is not unusual for a pumping station to be located in residential areas where an associated emergency generator has been installed as an integral part of the station. Portable generators have also seen increased use in recent years. Generators used for standby power will normally be the gasoline, diesel, or gas-turbine types, because these can be started immediately.

Note: Most electrical utility companies operate with reliability in excess of +90%. However, even a momentary loss of electrical power to plant operations cannot, in many instances, be tolerated. Therefore, standby electrical generators are important in maintaining plant operations. One of the main reasons why standby power is installed in plants is to provide emergency lighting for safe egress in the event of a failure of the utility supply. Exit lights, stairway lighting, and a portion of the corridor lighting systems are typically connected to the standby generator.

Fire and safety equipment often is connected to the standby power system to assist in emergency operations. Fire pumps, communications systems, fire detection and alarm systems, and security systems remain operational in the event of a disruption of the normal electrical supply.

Finally, critical mechanical equipment, such as pumps, is normally connected to the standby power system to protect the facility from damage if the equipment is out of service during an electrical outage.

Generators can be designed to supply small amounts of power or they can be designed to supply many thousands of kilowatts of power. In addition, generators may be designed to supply either direct current or alternating current.

6.24.2 DC Generators

A DC generator is a rotating machine that converts mechanical energy into electrical energy. This conversion is accomplished by rotating an armature that carries conductors in a magnetic field, inducing an EMF in the conductors. As stated previously, in order for an EMF to be induced in the conductors, a relative motion must always exist between the conductors and the magnetic field in such a manner that conductors cut through the field. In most DC generators, the armature is the rotating member and the field is the stationary member. A mechanical force is applied to the shaft of the rotating member to cause the relative motion. When mechanical energy is put into the machine in the form of a mechanical force or twist on the shaft, causing the shaft to turn at a certain speed, electrical energy in the form of voltage and current is delivered to the external load circuit.

Important Point: Mechanical power must be applied to the shaft constantly so long as the generator is supplying electrical energy to the external load circuit.

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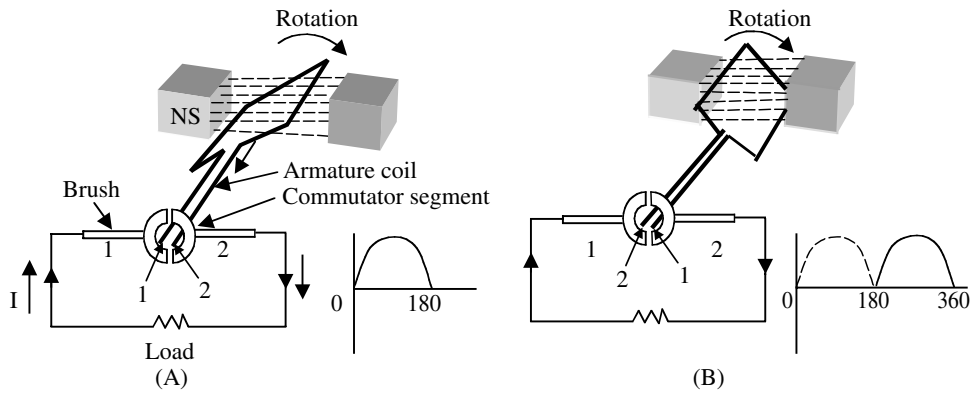

FIGURE 6.86 Basic operation of a DC generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

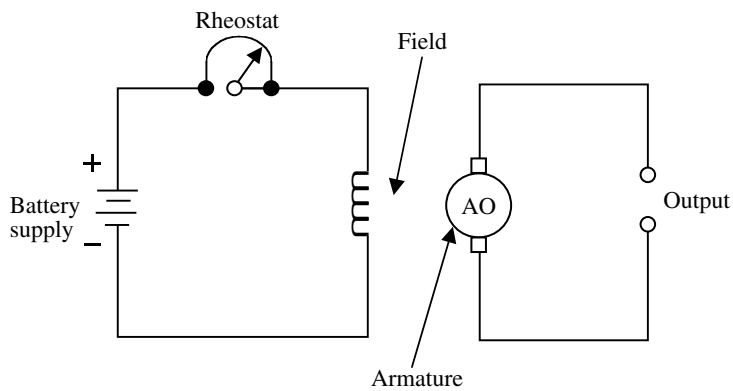

FIGURE 6.87 Separately excited DC generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

To gain a basic understanding of the operation of a DC generator, consider the following explanation.

A simple DC generator consists of an armature coil with a single turn of wire (see Figure 6.86A and Figure 6.86B). (Note: The armature coils used in large DC machines are usually wound in their final shape before being put on the armature. The sides of the preformed coil are placed in the slots of the laminated armature core.) This armature coil cuts across the magnetic field to produce voltage. If a complete path is present, current will move through the circuit in the direction shown by the arrows (see Figure 6.86A). In this position of the coil, commutator segment 1 is in contact with brush 1, while commutator segment 2 is in contact with brush 2. As the armature rotates a half turn in a clockwise direction, the contacts between the commutator segments and the brushes are reversed (see Figure 6.86B). At this moment, segment 1 is in contact with brush 2 and segment 2 is in contact with brush 1. Because of this commutator action, that side of the armature coil that is in contact with either of the brushes is always cutting across the magnetic field in the same direction. Thus, brushes 1 and 2 have constant polarity, and a pulsating DC current is delivered to the external load circuit.

Note: In DC generators, voltage induced in individual conductors is alternating current. It is converted to direct current (rectified) by the commutator that rotates in contact with carbon brushes so that current generated is in one direction, or direct current.

There are several different types of DC generators. They take their names from the type of field excitation used (i.e., they are classified according to the manner in which the field windings are connected to the armature circuit). For example, when the generator's field is excited (or supplied) from a separate DC source (such as a battery) other than its own armature, it is called a separately excited DC generator (see Figure 6.87).

A shunt generator (self-excited) has its field windings connected in series with a rheostat, across the armature in

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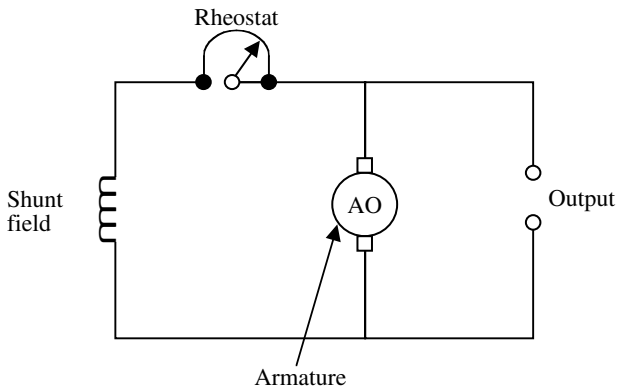

FIGURE 6.88 DC shunt generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

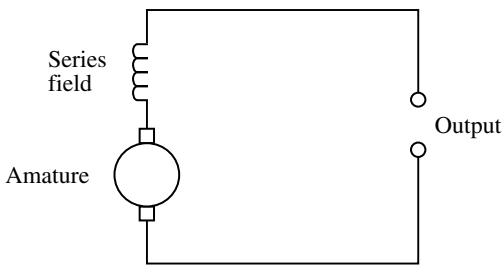

FIGURE 6.89 DC series generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

shunt with the load, as shown in Figure 6.88. The shunt generator is widely used in industry.

A series generator (self-excited) has its field windings connected in series with the armature and load, as shown in Figure 6.89. Series generators are seldom used.

Compound generators (self-excited) contain both series and shunt field windings, as shown in Figure 6.90. Compound generators are widely used in industry.

Note: Central generating stations increased in size along with number and power distribution distances. As a result, DC generating systems, because of the high power losses in long DC transmission lines, were replaced by AC generating systems to reduce power transmission costs.

6.24.3 AC Generators

Most electric power utilized today is generated by AC generators (also called alternators). They are made in many different sizes, depending on their intended use. Regardless of size, all generators operate on the same

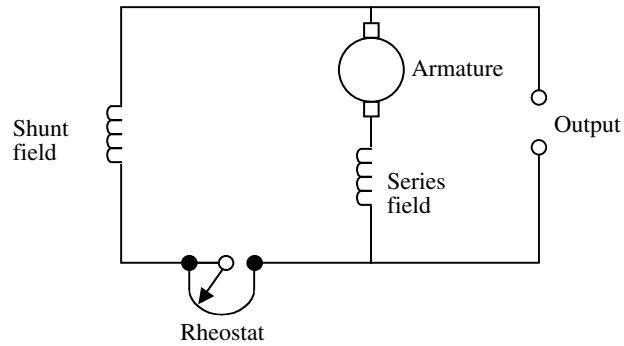

FIGURE 6.90 DC compound generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

basic principle — a magnetic field cutting through conductors, or conductors passing through a magnetic field. They are (1) a group of conductors in which the output voltage is generated, and (2) a second group of conductors through which direct current is passed to obtain an electromagnetic field of fixed polarity. The conductors in which the electromagnetic field originates are always referred to as the field windings.

In addition to the armature and field, there must also be motion between the two. To provide this, AC generators are built in two major assemblies: the stator and the rotor. The rotor rotates inside the stator.

The revolving-field AC generator (see Figure 6.91) is the most widely used type. In this type of generator, direct current from a separate source is passed through windings on the rotor by means of sliprings and brushes. (Note: Sliprings and brushes are adequate for the DC field supply because the power level in the field is much smaller than in the armature circuit.) This maintains a rotating electromagnetic field of fixed polarity. The rotating magnetic field, following the rotor, extends outward and cuts through the armature windings imbedded in the surrounding stator. As the rotor turns, AC voltages are induced in the windings. This is because magnetic fields of first one polarity and then the other cut through them. Since the output power is taken from stationary windings, the output may be connected through fixed output terminals T1 and T2 in Figure 6.91. This is advantageous, since there are no sliding contacts and the whole output circuit is continuously insulated.

Important Point In AC generators, frequency and electromagnetic wave cycles per second depend on how fast the rotor turns and the number of electromagnetic field poles. Voltage generated depends on the rotor speed, number of coils in the armature and strength of the magnetic field.

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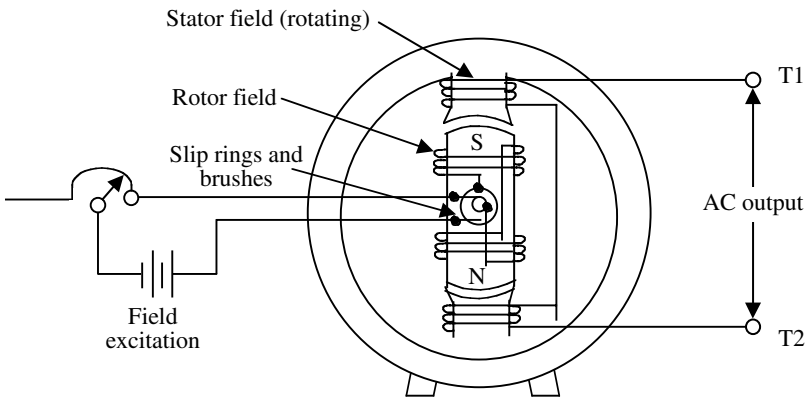

FIGURE 6.91 Essential parts of a rotating field AC generator. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.24.4 Motors

At least 60% of the electrical power fed to a typical waterworks and/or wastewater treatment plant is consumed by electric motors. One thing is certain: there is an almost endless variety of tasks that electric motors perform in water and wastewater treatment.

An electric motor is a machine used to change electrical energy to mechanical energy to do the work. (Note: Recall that a generator does just the opposite; that is, a generator changes mechanical energy to electrical energy.)

We previously pointed out that when a current passes through a wire, a magnetic field is produced around the wire. If this magnetic field passes through a stationary magnetic field, the fields either repel or attract, depending on their relative polarity. If both are positive or negative, they repel. If they are opposite polarity, they attract.

Applying this basic information to motor design, an electromagnetic coil, the armature, rotates on a shaft. The armature and shaft assembly are called the rotor. The rotor is assembled between the poles of a permanent magnet, and each end of the rotor coil (armature) is connected to a commutator also mounted on the shaft. A commutator is composed of copper segments insulated from the shaft and from each other by an insulting material. As like poles of the electromagnet in the rotating armature pass the stationary permanent magnet poles, they are repelled, continuing the motion. As the opposite poles near each other, they attract, continuing the motion.

6.24.4.1 DC Motors

The construction of a DC motor is essentially the same as that of a DC generator. However, it is important to remember that the DC generator converts mechanical energy into the electrical energy back into mechanical energy. A DC generator may be made to function as a motor by applying a suitable source of DC voltage across the normal output electrical terminals.

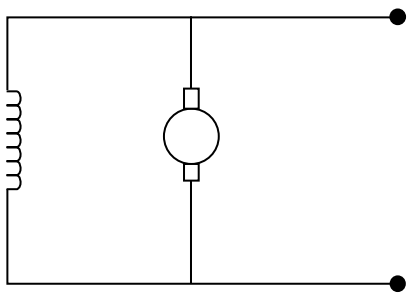

FIGURE 6.92 DC shunt motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

There are various types of DC motors, depending on the way the field coils are connected. Each has characteristics that are advantageous under given load conditions.

Shunt motors (see Figure 6.92) have the field coils connected in parallel with the armature circuit. This type of motor, with constant potential applied, develops variable torque at an essentially constant speed, even under changing load conditions. Such loads are found in machine-shop equipment, such as lathes, shapes, drills, and milling machines.

Series motors (see Figure 6.93) have the field coils connected in series with the armature circuit. This type of motor, with constant potential applied, develops variable torque, but its speed varies widely under changing load conditions. The speed is low under heavy loads, but becomes excessively high under light loads. Series motors are commonly used to drive electric hoists, winches, cranes, and certain types of vehicles (e.g., electric trucks). In addition, series motors are used extensively to start internal combustion engines.

Compound motors (see Figure 6.94) have one set of field coils in parallel with the armature circuit, and another

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FIGURE 6.93 DC series motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

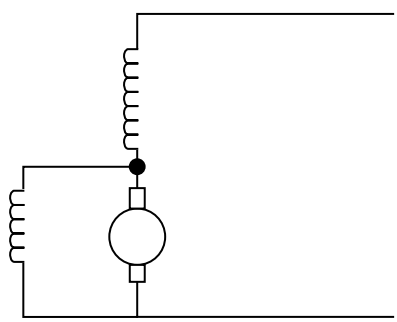

FIGURE 6.94 DC compound motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

set of field coils in series with the armature circuit. This type of motor is a compromise between shunt and series motors. It develops an increased starting torque over that of the shunt motor, and it has less variation in speed than the series motor.

The speed of a DC motor is variable. It is increased or decreased by a rheostat connected in series with the field or in parallel with the rotor. Interchanging either the rotor or field winding connections reverses direction.

6.24.4.2 AC Motors

AC voltage can be easily transformed from low voltages to high voltages or vice versa, and can be moved over a much greater distance without too much loss in efficiency. Most of the power generating systems today produce alternating current. Thus, it logically follows that a great majority of the electrical motors utilized today are designed to operate on alternating current. There are other advantages in the use of AC motors besides the wide availability of AC power. In general, AC motors are less expensive than DC motors. Most types of AC motors do not employ brushes and commutators. This eliminates many problems of maintenance and wear and eliminates dangerous sparking.

AC motors are manufactured in many different sizes, shapes, and ratings, for use on an even greater number of jobs. They are designed for use with either polyphase or single-phase power systems.

This chapter cannot possibly cover all aspects of the subject of AC motors. It will deal mainly with the operating principles of the two most common types: the induction and the synchronous motor.

6.24.4.2.1 Induction Motors

The induction motor is the most commonly used type of AC motor because of its simple, rugged construction and good operating characteristics. It consists of two parts: the stator (stationary part) and the rotor (rotating part).

The most important type of polyphase induction motor is the three-phase (3-θ) motor.

Important Note: A three-phase (3-θ) system is a combination of three single-phase (1-θ) systems. In a 3-θ balanced system, the power comes from an AC generator that produces 3 separate but equal voltages, each of which is out of phase with the other voltages by 120°. Although 1-θ circuits are widely used in electrical systems, most generation and distribution of AC current is 3-θ.

The driving torque of both DC and AC motors is derived from the reaction of current-carrying conductors in a magnetic field. In the DC motor, the magnetic field is stationary and the armature, with its current-carrying conductors, rotates. The current is supplied to the armature through a commutator and brushes.

In induction motors, the rotor currents are supplied by electromagnet induction. The stator windings, connected to the AC supply, contain two or more out-of-time-phase currents that produce corresponding MMFs. These MMFs establish a rotating magnetic field across the air gap. This magnetic field rotates continuously at constant speed regardless of the load on the motor. The stator winding corresponds to the armature winding of a DC motor or to the primary winding of a transformer. The rotor is not connected electrically to the power supply.

The induction motor derives its name from the fact that mutual induction (or transformer action) takes place between the stator and the rotor under operating conditions. The magnetic revolving field produced by the stator cuts across the rotor conductors, inducing a voltage in the conductors. This induced voltage causes rotor current to flow. Motor torque is therefore developed by the interaction of the rotor current and the magnetic revolving field.

6.24.4.2.2 Synchronous Motors

Like induction motors, synchronous motors have stator windings that produce a rotating magnetic field. Unlike the induction motor, the synchronous motor requires a

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separate source of DC from the field. It also requires special starting components. These include a salient-pole field with starting grid winding. The rotor of the conventional type synchronous motor is essentially the same as the salient-pole AC generator's. The stator windings of induction and synchronous motors are essentially the same.

In operation, the synchronous motor rotor locks into step with the rotating magnetic field and rotates at the same speed. If the rotor is pulled out of step with the rotating stator field, no torque is developed and the motor stops. Since a synchronous motor develops torque only when running at synchronous speed, it is not self-starting and needs some device to bring the rotor to synchronous speed. For example, a synchronous motor may be started rotating with a DC motor on a common shaft. After the motor is brought to synchronous speed, AC current is applied to the stator windings. The DC starting motor now acts as a DC generator that supplies DC field excitation for the rotor. The load then can be coupled to the motor.

6.24.4.2.3 Single-Phase Motors

Single-phase (1-θ) motors are so called because their field windings are connected directly to a single-phase source. These motors are used extensively in fractional horsepower sizes in commercial and domestic applications. The advantages of using 1-θ motors in small sizes are that they are less expensive to manufacture than other types, and they eliminate the need for 3-θ AC lines. 1-θ motors are used in equipment such as fans, refrigerators, portable drills, and grinders.

A 1-θ induction motor with only one stator winding and a cage rotor is like a 3-θ induction motor with a cage rotor except that the 1-θ motor has no magnetic revolving field at start and no starting torque. If the rotor is brought up to speed by external means, the induced currents in the rotor will cooperate with the stator currents to produce a revolving field, causing the rotor to continue to run in the direction that it was started.

Several methods are used to provide the 1-θ induction motor with starting torque. These methods identify the motor as split-phase, capacitor, shaded-pole, and repulsion-start induction motor.

Another class of single-phase motors is the AC series (universal) type. Only the more commonly used types of single-phase motors are described. These include the:

1. Split-phase motor
2. Capacitor motor
3. Shaded-pole motor
4. Repulsion-start motor
5. AC series motor.

6.24.4.2.3.1 Split-Phase Motors

The split-phase motor (see Figure 6.95) has a stator composed of slotted lamination that contains a starting winding and a running winding.

Note: If two stator windings of unequal impedance are spaced 90 electrical degrees apart but connected in parallel to a single-phase source, the field produced will appear to rotate. This is the principle of **phase splitting**.

The starting winding has fewer turns and smaller wire than the running winding; therefore it has higher resistance and less reactance. The main winding occupies the lower half of the slots and the starting winding occupies the upper half. When the same voltage is applied to both windings, the current in the main winding lags behind the current in the starting winding. The angle between the main and starting windings is enough phase difference to provide a weak rotating magnetic field to produce a starting torque. When the motor reaches a predetermined speed, usually 75% of synchronous speed, a centrifugal switch mounted on the motor shaft opens, disconnecting the starting winding.

Because it has a low starting torque, fractional-horsepower split-phase motors are used in a variety of equipment such as washers, oil burners, ventilating fans, and woodworking machines. Interchanging the starting winding leads can reverse the direction of rotation of the split-phase motor.

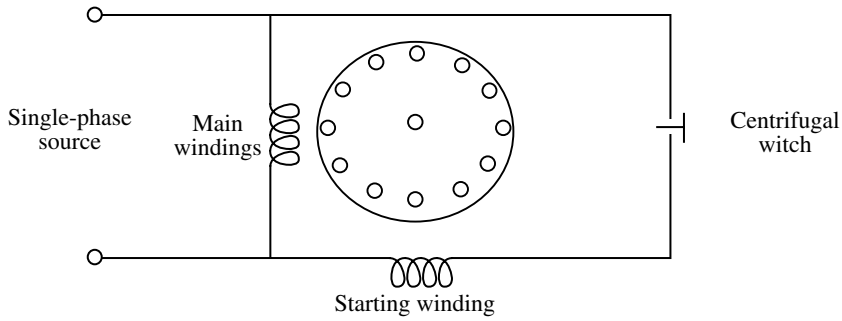

FIGURE 6.95 Split-phase motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

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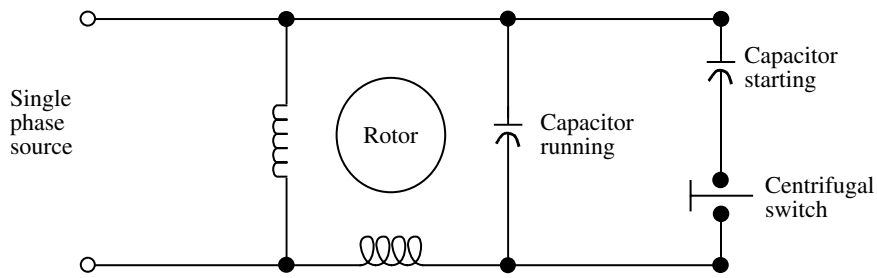

FIGURE 6.96 Capacitor motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.24.4.2.3.2 Capacitor Motors

The capacitor motor is a modified form of split-phase motor, having a capacitor in series with the starting winding. The capacitor motor operates with an auxiliary winding and series capacitor permanently connected to the line (see Figure 6.96). The capacitance in series may be of one value for starting and another value for running. As the motor approaches synchronous speed, the centrifugal switch disconnects one section of the capacitor.

If the starting winding is cut out after the motor has increased in speed, the motor is called a capacitor-start motor. If the starting winding and capacitor are designed to be left in the circuit continuously, the motor is called capacitor-run motor. Capacitor motors are used to drive grinders, drill presses, refrigerator compressors, and other loads that require relatively high starting torque. Interchanging the starting winding leads may reverse the direction of rotation of the capacitor motor.

6.24.4.2.3.3 Shaded-Pole Motor

A shaded-pole motor employs a salient-pole stator and a cage rotor. The projecting poles on the stator resemble those of DC machines. The difference is that the entire magnetic circuit is laminated and a portion of each pole is split to accommodate a short-circuited coil called a shading coil (see Figure 6.97). The coil is usually a single band or strap of copper. The effect of the coil is to produce a small sweeping motion of the field flux from one side of the pole piece to the other as the field pulsates. This slight shift in the magnetic field produces a small starting torque. Thus, shaded-pole motors are self-starting. This motor is generally manufactured in very small sizes, up to 1/20 hp, for driving small fans, small appliances, and clocks.

In operation, during that part of the cycle when the main pole flux is increasing, the shading coil is cut by the flux; the resulting induced EMF and current in the shading coil tend to prevent the flux from rising readily through it. The greater portion of the flux rises in that portion of the pole that is not near the shading coil. When the flux reaches its maximum value, the rate of change of flux is zero, and the voltage and current in the shading coil are zero. At this

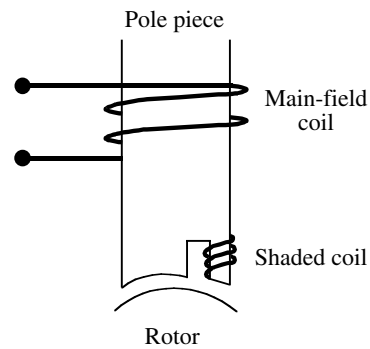

FIGURE 6.97 Shaded pole. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

time, the flux is distributed more uniformly over the entire pole face. Then as the main flux decreases toward zero, the induced voltage and current in the shading coil reverse their polarity, and the resulting MMF tends to prevent the flux from collapsing through the iron in the region of the shading coil. The result is that the main flux first rises in the unshaded portion of the pole and later in the shaded portion. This action is equivalent to a sweeping movement of the field across the pole face in the direction of the shaded pole. This moving field cuts the rotor conductors and the force exerted on them causes the rotor to turn in the direction of the sweeping field. The shaded-pole method of starting is used in very small motors, up to about 1/25 hp, for driving small fans, small appliances, and clocks.

6.24.4.2.3.4 Repulsion-Start Motor

Like a DC motor, the repulsion-start motor has a form-wound rotor with commutator and brushes. The stator is laminated and contains a distributed single-phase winding. In its simplest form, the stator resembles the single-phase motor. In addition, the motor has a centrifugal device that removes the brushes from the commutator and places a short-circuiting ring around the commutator. This action occurs at about 75% of synchronous speed. Thereafter, the motor operates with the characteristics of the single-phase induction motor. This type of motor is made in sizes

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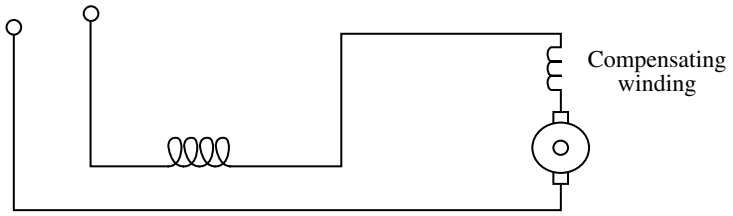

FIGURE 6.98 AC series motor. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

ranging from 1/2 to 15 hp and is used in applications requiring a high starting torque.

6.24.4.2.3.5 AC Series Motor

The AC series motor will operate on either AC or DC circuits. When an ordinary DC series motor is connected to an AC supply, the current drawn by the motor is low due to the high series-field impedance. The result is low running torque. To reduce the field reactance to a minimum, AC series motors are built with as few turns as possible. Armature reaction is overcome by using compensating windings (see Figure 6.98) in the pole pieces.

As with DC series motors, in an AC series motor the speed increases to a high value with a decrease in load. The torque is high for high armature currents so that the motor has a good starting torque. AC series motors operate more efficiently at low frequencies.

Fractional horsepower AC series motors are called universal motors. They do not have compensating windings. They are used extensively to operate fans and portable tools, such as drills, grinders, and saws.

6.24.5 Transformers

A transformer is an electric control device (with no moving parts) that raises or lowers voltage or current in an electric distribution system. The basic transformer consists of two coils electrically insulated from each other and wound upon a common core (see Figure 6.99). Magnetic coupling is used to transfer electric energy from one coil to another. The coil that receives energy from an AC source, is called the primary. The coil that delivers energy to an AC load is called the secondary. The core of transformers used at low frequencies is generally made of magnetic material, usually laminated sheet steel. Cores of transformers used at higher frequencies are made of powdered iron and ceramics or nonmagnetic materials. Some coils are simply wound on nonmagnetic hollow forms, such as cardboard or plastic, so that the core material is actually air.

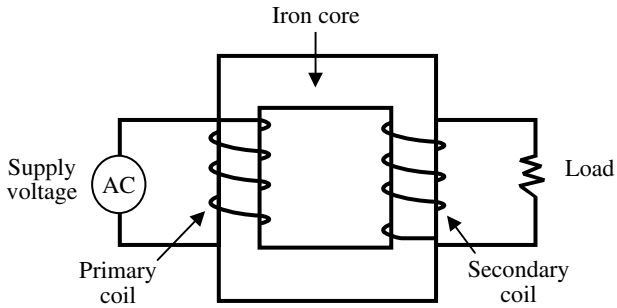

FIGURE 6.99 Basic transformer. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

In operation, an alternating current will flow when an AC voltage is applied to the primary coil of a transformer. This current produces a field of force that changes as the current changes. The changing magnetic field is carried by the magnetic core to the secondary coil, where it cuts across the turns of that coil. In this way, an AC voltage in one coil is transferred to another coil, even though there is no electrical connection between them. The primary voltage and the number of turns on the primary determine the number of lines of force available in the primary, each turn producing a given number of lines. If there are many turns on the secondary, each line of force will cut many turns of wire and induce a high voltage. If the secondary contains only a few turns, there will be few cuttings and low induced voltage. The secondary voltage depends on the number of secondary turns as compared with the number of primary turns. If the secondary has twice as many turns as the primary, the secondary voltage will be twice as large as the primary voltage. If the secondary has half as many turns as the primary, the secondary voltage will be one-half as large as the primary voltage.

Important Point: The voltage on the coils of a transformer is directly proportional to the number of turns on the coils.

A voltage ratio of 1:4 means that for each volt on the primary, there are 4 V on the secondary. This is called a step-up transformer. A step-up transformer receives a low voltage on the primary and delivers a high voltage from the secondary. A voltage ratio of 4:1 means that for 4 V on the primary, there is only 1 V on the secondary. This is called a step-down transformer. A step-down transformer receives a high voltage on the primary and delivers a low voltage from the secondary.

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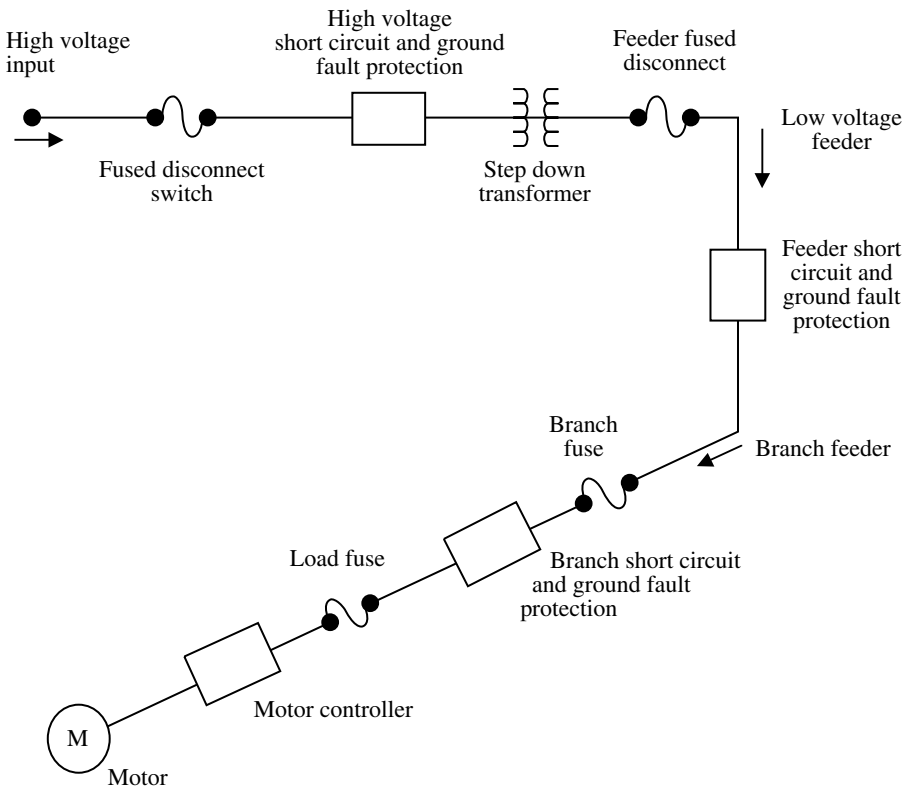

FIGURE 6.100 Motor power distribution system. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.24.6 Power Distribution System Protection

Interruptions are very rare in a power distribution system that has been properly designed. Still, protective devices are necessary because of the load diversity. Most installations are quite complex. In addition, externally caused variations might overload them or endanger personnel.

Figure 6.100 shows the general relationship between protective devices and different components of a complete system. Each part of the circuit has its own protective device or devices that protect not only the load, but also the wiring and control devices themselves. These disconnect and protective devices are described in the following sections.

6.24.6.1 Fuses

The passage of an electric current produces heat. The larger the current, the more heat is produced. In order to prevent large currents from accidentally flowing through expensive apparatus and burning it up, a *fuse* is placed directly into the circuit, as in Figure 6.100, and forms a part of the circuit through which all the current must flow.

Key Point: A fuse is a thin strip of easily melted material. It protects a circuit from large currents by melting quickly and breaking the circuit.

The fuse will permit currents smaller than the fuse value to flow, but will melt and therefore break the circuit if a larger, dangerous current ever appears. For instance, a dangerously large current will flow when a short circuit occurs. A short circuit is usually caused by an accidental connection between two points in a circuit, which offer very little resistance to the flow of electrons. If the resistance is small, there will be nothing to stop the flow of the current, and the current will increase enormously. The resulting heat generated might cause a fire. However, if the circuit is protected by a fuse, the heat caused by the short-circuit current will melt the fuse wire, thus breaking the circuit and reducing the current to zero.

The number of amps of current that can flow through before they melt and break the circuit rates the fuses. Thus, we have 10-A, 15-A, 20-A, 30-A etc., fuses. We must be careful that any fuse inserted in a circuit be rated low enough to melt, or "blow," before the apparatus is damaged. For example, in a plant building wired to carry a current of 10 A, it is best to use a fuse no larger than 10 A so that a current larger than 10 A could never flow.

Some equipment, such as electric motors, requires more current during starting than for normal running. Thus, fast-time or medium-time fuse rating that will give running protection might blow during the initial period

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when high starting current is required. Delayed action fuses are used to handle these situations.

6.24.6.2 Circuit Breakers

Circuit breakers are protective devices that open automatically at a preset ampere rating to interrupt an overload or short circuit. Unlike fuses, they do not require replacement when they are activated. They are simply reset to restore power after the overload has been cleared.

Key Point: A circuit breaker is designed to break the circuit and stop the current flow when the current exceeds a predetermined value.

Circuit breakers are made in both plug-in and bolt-on designs. Plug-in breakers are used in load centers. Bolt-ons are used in panelboards and exclusively for high interrupting current applications.

Circuit breakers are rated according to current and voltage, as well as short circuit interrupting current. A single handle opens or closes contacts between two or more conductors. Breakers are single-pole, but can be ganged single-pole units that form double-or-triple-pole devices opened with a single handle.

Several types of circuit breakers are commonly used. They may be thermal, magnetic, or a combination of the two. Thermal breakers are tripped when the temperature rises because of heat created by the overcurrent condition. Bimetallic strips provide the time delay for overload protection. Magnetic breakers operate on the principle that a sudden current rise creates enough magnetic field to turn an armature, tripping the breaker and opening the circuit. Magnetic breakers provide the instantaneous action needed for short circuit protection. Thermal-magnetic breakers combine features of both types of breakers.

Magnetic breakers are also used in circumstances where ambient temperature might adversely affect the action of a thermal breaker.

An important feature of the circuit breaker is its arc chutes, which enable the breaker to extinguish very hot arcs harmlessly. Some circuit breakers must be reset by hand, while others reset themselves automatically. When the circuit breaker is reset, if the overload condition still exists, the circuit breaker will trip again to prevent damage to the circuit.

6.24.6.3 Control Devices

Control devices are those electrical accessories (switches and relays) that govern the power delivered to any electrical load.

In its simplest form, the control applies voltage to, or removes it from, a single load. In more complex control systems, the initial switch may set into action other control devices (relays) that govern motor speeds, servomechanisms, temperatures, and numerous other pieces of equipment. In fact, all electrical systems and equipment are controlled in some manner by one or more controls. A controller is a device or group of devices that serves to govern, in some predetermined manner, the device to which it is connected.

In large electrical systems, it is necessary to have a variety of controls for operation of the equipment. These controls range from simple pushbuttons to heavy-duty contactors that are designed to control the operation of large motors. The pushbutton is manually operated while a contactor is electrically operated.

6.25 CHAPTER REVIEW QUESTIONS AND PROBLEMS

6.1. Another name for an AC generator is _____.
6.2. What is electromagnetic induction?
6.3. An alternator converts _____ energy into _____ energy.
6.4. A step-up transformer _____ the voltage and _____ the current. A step-down transformer _____ the voltage and _____ the current.
6.5. What is the purpose of a fuse?
6.6. An electrical circuit with a conductance of 5 mho would have a resistance of _____.
6.7. Electrons move about the nucleus of an atom in paths that are called _____.
6.8. The nucleus of an atom consists of particles called _____ and _____.
6.9. What three factors affect the resistance in a circuit?
6.10. What is the difference between direct and alternating current?
6.11. What are the points of maximum attraction on a magnet?
6.12. What is a magnetic field?
6.13. What are the three general groups of magnets?
6.14. What method of producing a voltage is used in batteries?
6.15. A _____ consists of _____ or more cells connected in series or parallel.
6.16. Explain the difference between a series and a parallel circuit.
6.17. The sum of all voltages in a series circuit is equal to:
6.18. For any total voltage rise in a circuit, there must be an equal total _____.

Refer to Figure 6.101 for Questions 6.19 through 6.23:

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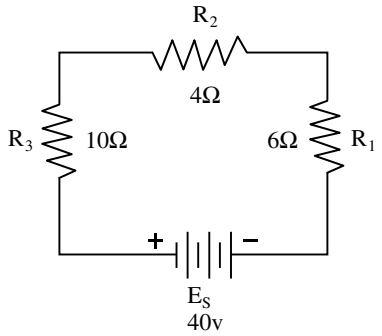

FIGURE 6.101 For Questions 6.19 to 6.23. (From Spellman, F.R. and Drinan, J., *Electricity,* Technomic Publ., Lancaster, PA, 2001.)

6.19. Is the direction of current flow clockwise or counterclockwise?

6.20. What is the value of I_T ?

6.21. What is the value of E dropped across R_1?

6.22. What is the power absorbed by R_2?

6.23. What is the value of P_T?

6.24. The equivalent resistance R_T of parallel branches is _____ than the smallest branch resistance since all the branches must take _____ current from the source than any one branch.

6.25. The resistance in ohms of a unit conductor or a given substance is called the _____.

6.26. The _____ is the standard unit of wire cross-sectional area used in most wire tables.

6.27. Which is smaller, a circular mil or a square mil?

6.28. Resistivity is the reciprocal of _____.

6.29. A No. 8 wire is _____ than No. 4 wire.

6.30. For every three-gauge sizes, the circular area of a wire _____.

6.31. What is the biggest advantage of using plastic insulation tape over other types of tape?

6.32. What is the relationship between flux density and magnetic field strength?

6.33. Permeability depends on what two factors?

6.34. Lines of force flow from the _____.

6.35. If a conductor is rotated faster in the magnetic field of an alternator, what will happen to the frequency of the voltage?

6.36. If the peak AC voltage across a resistor is 200 V, what is the rms voltage?

6.37. What is electromagnetic induction?

6.38. When an AC voltage is impressed across a coil, the resulting current is an _____ current. This changing current produces changing fields of force that _____ the wires of the coil. These cuttings induce a _____ EMF in the coil.

6.39. The inductance of a coil is a measure of its ability to produce a _____ EMF when the current through it is changing.

6.40. What characteristics of electric current results in self-inductance?

6.41. An increase in the cross-sectional area of a coil will_____ inductance.

6.42. An increase in the permeability of a coil will _____ inductance.

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7 Hydraulic Machines: Pumps

Pumping facilities are required wherever gravity can't be used to supply water to the distribution system under sufficient pressure to meet all service demands.

Regarding wastewater, pumps are used to lift or elevate the liquid from a lower elevation to an adequate height at which it can flow by gravity or overcome hydrostatic head. There are many pumping applications at a wastewater treatment facility. These applications include pumping of (1) raw or treated wastewater, (2) grit, (3) grease and floating solids, (4) dilute or well-thickened raw sludge, or digested sludge, (sludge or supernatant return), and (5) dispensing of chemical solutions. Pumps and lift stations are used extensively in the collection system. Each of the various pumping applications is unique and requires specific design and pump selection considerations.

Where pumping is necessary, it accounts for most of the energy consumed in water supply and/or wastewater treatment operations.[1]

7.1 INTRODUCTION

Early in the preliminary engineering design phase it is important to establish the hydraulic grade line across the plant. This is because both the proper selection of the plant site elevation and the suitability of the site (to accommodate all unit processes requiring specific water elevations and depths of structures) depend on this consideration.

Kawamura points out that the importance of designing the correct hydraulic grade line across the plant can best be understood through example. Consider, for example, the initial design of a conventional water treatment plant. Most conventional water treatment plants required 16 to 17 ft of headloss across the plant. This means that a difference of 16 to 17 ft must exist between the water level at the head of the plant and the high water level in the clearwell, which is the end of the treatment plant unit process train. Treatment plants using preozonation, as well as postozonation and granular activated carbon adsorption processes, require almost 25 ft of available head across the plant. Under these circumstances, if the plant site is flat, the following parameters must be considered:

1. The high water level in the clearwell must be set at ground level because of the groundwater table.
2. The water level at the head of the unit process train must be 25 ft above the ground level.
3. The majority of the unit processes in the first half of the process train must be elevated unless a pumping station is included in the unit process train.

A flat and level site is not the best choice for this type of treatment plant. The ideal plant site will have a 3 to 5% one-way slope and a ground elevation that satisfies the necessary elevations.[2]

The importance of a water or wastewater treatment plant's hydraulic grade line is obvious — flow through the plant site is aided by hydraulic gradient via gravity. However, even when careful consideration has been placed on ensuring the proper hydraulic grade line across the plant, flow from one unit process to another cannot be accomplished exclusively by gravity. When the flow needs to be lifted or elevated from a lower elevation to an adequate height, at which it can flow by gravity or overcome hydrostatic head, water or wastewater-pumping stations must be included. There are many pumping applications in water and wastewater operations. These applications include pumping of:

1. Raw or treated water or wastewater
2. Grit
3. Grease and floating solids
4. Dilute or well-thickened raw sludge, or digested sludge (biosolids)
5. Sludge or supernatant return
6. Dispensing of chemical solutions

Pumps and lift stations are also used extensively in the water distribution and wastewater collections systems.

Note: Each of the various pumping applications is unique and requires specific design and pump selection considerations.

Note: Even though pumps are used extensively in both water and wastewater operations, water may also be distributed by gravity, pumps, or pumps in conjunction with on-line storage. In

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water distribution, pumping with storage is the most common method of distribution.

7.2 ARCHIMEDES' SCREW

At the top of the short list comprising the names associated with the greatest achievements in science and the arts are Aristotle, Michelangelo, Da Vinci, Newton, and Einstein. You may have noticed that one name has been left off this list — Archimedes. While Archimedes may be recognized as one of the greatest geniuses of all time, many are confused about what he actually did. As Stein points out, all we may well remember is, "something about running naked out of his bath crying 'Eureka, Eureka.'"

We were just as uninformed about Archimedes' accomplishments until we began the research for this text. We were genuinely astonished at the magnitude, the sheer number of Archimedes' scientific accomplishments and their profound impact on today's world.[3]

Contrary to appearances, the goal of this chapter is not make Archimedes' most mathematically significant discoveries (of which there are so many) the main topic of our discussion. Archimedes is included in our discussion of pumps to enrich the user's experience in reading this text and to enlarge the reader's historical perspective.

Few engineered artifacts are as essential as pumps in the development of the culture that our western civilization enjoys. Such machines affect every facet or our daily lives. Even before the time of Archimedes (before 287 B.C.), ancient civilizations requiring irrigation and essential water supplies used crude forms of pumps that (with their design refinements) are still in use even today.

Note: Exactly how significant pumps are to civilization can be appreciated when you consider that of all the machines currently used, the pump is the second most frequently used. Only the electric motor exceeds the use of the pump.

Krutzsch[4] fittingly points out that "only the sail can contend with the pump for the title of the earliest invention for the conversion of natural energy to useful work, and it is doubtful that the sail takes precedence." In reality, because the sail is not a machine, we can state unequivocally that the pump stands "essentially unchallenged as the earliest form of machine which substituted natural energy for muscular effort in the fulfillment of man's needs."

As historical records differ among ancient civilizations (cultures), and as each culture commonly supplied solutions to individual problems, several names and forms of the earliest pumps are known. Some cultures described the earliest pumps as water wheels, Persian wheels, or norias (i.e., water wheels of various design; a noria is a water wheel with buckets attached to its rim that are used to raise water from a stream, especially for transferal to an irrigation trough). Even today, water wheels of similar design have continued in use in parts of the Orient.

Where does Archimedes come in? The Archimedean screw is probably the best known of the early pumps. In fact, the principle of the Archimedean screw is still being used today. Figure 7.1 shows a system application of an Archimedes' screw lift pumps as applied in wastewater treatment.

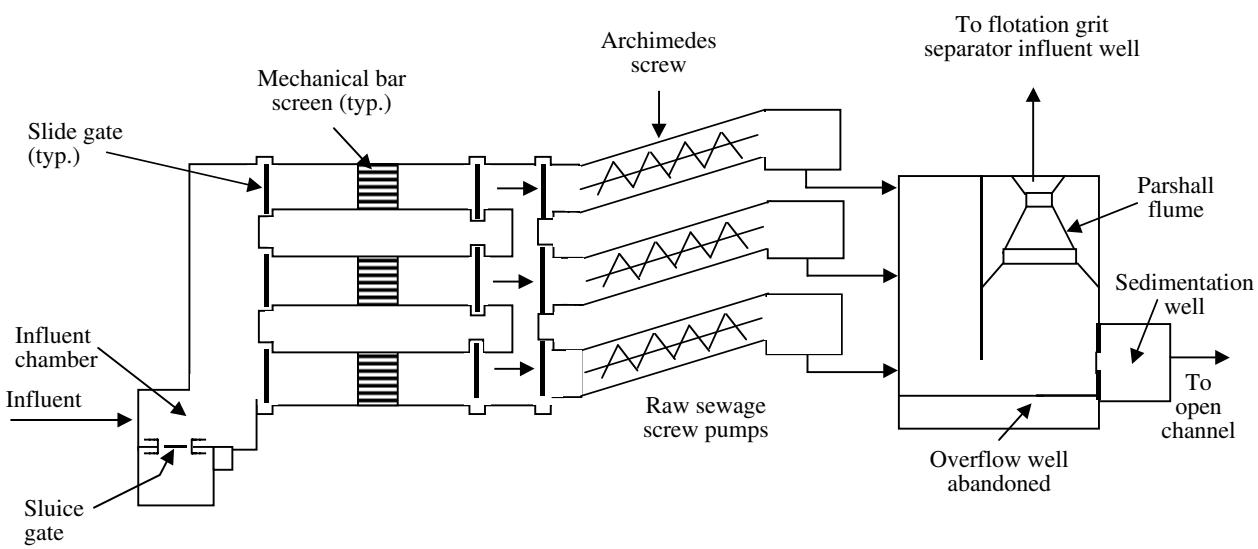

FIGURE 7.1 Archimedes screw lift pumps as applied in wastewater treatment. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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Let us take an even closer look at Archimedes' invention (a modern view that includes modern applications). As previously stated and as shown in Figure 7.1, Archimedean screw pumps are occasionally used for raw wastewater pumping applications. According to Benjes and Foster, these units are "advantageous in that they do not require a conventional wet well and they are self-compensating in that they automatically pump the liquid received regardless of quantity as long as it does not exceed the design capacity of the pump." In addition, no special drive equipment is required. Moreover, the total operating head of a screw pump installation is less than for those pumps that require conventional suction and discharge piping. Screw pumps are limited by pumping head and not used for lifts more than 25 ft.[5]

7.3 PUMPING HYDRAULICS

A water pumping system can be equated with that of the human circulatory system.

In human beings, the flood, kept in motion by the pumping of the heart, circulates through a series of vessels. The heart is actually a double pump: the right side pumps blood to the lungs and the left side pumps blood to the rest of the body.

Both of these hydraulic "machines," the heart and the pump, perform very vital functions.

7.3.1 Definitions[6]

There are several basic terms and symbols used in discussing pumping hydraulics that should be known and understood by those that must operate and maintain plant-pumping facilities. The most important terms are included in this section.

Absolute pressure the pressure of the atmosphere on a surface. At sea level, a pressure gauge with no external pressure added will read 0 psig. The atmospheric press is 14.7 psia (again, at sea level). If the gauge pressure (psig) reads 15 psig, the absolute pressure (psia) will be 15 + 14.7, or 29.7 psia.

Acceleration due to gravity (g) the rate at which a falling body gains speed. The acceleration due to gravity is 32 ft/sec/sec. This simply means that a falling body or fluid will increase the speed at which it is falling by 32 feet/sec every second that it continues to fall.

Atmospheric pressure the pressure exerted on a surface area by the weight of the atmosphere is atmospheric pressure, which at sea level is 14.7 psi, or 1 atm. At higher altitudes, the atmospheric pressure decreases. At locations below sea level, the atmospheric pressure rises (see

TABLE 7.1
Atmospheric Pressure at Various Altitudes

Altitude	Barometric Pressure	Equivalent Head
–1000 ft	15.2 psi	35.2 ft
Sea Level	14.7 psi	34.0 ft
1500 ft	13.9 psi	32.2 ft
3000 ft	13.2 psi	30.5 ft
5000 ft	12.2 psi	28.3 ft
7000 ft	11.3 psi	26.2 ft
8000 ft	10.9 psi	25.2 ft

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

Cavitation an implosion of vapor bubbles in a liquid inside a pump caused by a rapid local pressure decrease occurring mostly close to or touching the pump casing or impeller. As the pressure reduction continues these bubbles collapse or implode. Cavitation may produce noises that sound like pebbles rattling inside the pump casing and may cause the pump to vibrate and to lose hydrodynamic efficiency. This effect contrasts with boiling, which happens when heat builds up inside the pump.

Continued serious cavitation may destroy even the hardest surfaces. Avoiding cavitation is one of the most important pump design criteria. Cavitation limits the upper and lower pump sizes, as well as the pump's peripheral impeller speed.

Cavitation may be caused by any of the following conditions:

1. Discharge heads are far below the pump's calibrated head at peak efficiency.
2. Suction lift is higher or suction head is lower than the manufacturer's recommendation.
3. Speeds are higher than the manufacturer's recommendation.
4. Liquid temperatures (thus, vapor pressure) are higher than that for which the system was designed.

Critical speed at this speed, a pump may vibrate enough to cause damage. Pump manufacturers try to design pumps with the first critical speed at least 20% higher or lower than rated speed. Second and third critical speeds usually don't apply in pump usage.

Cross-sectional area (A) the area perpendicular to the flow which the load in a channel or pipe occupies (see Figure 7.2).

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FIGURE 7.2 Cross-sectional area. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Density the mass per unit volume measured in pounds per cubic foot at 68°F or in grams per milliliter at 4°C.

Discharge pressure the pressure measured at the pump's discharge nozzle. Measurements may be stated in:

Psig	Bars
Psig	Bars
kg/cm^2	Kilopascals

Displacement the capacity, or flow of a pump. This measurement, primarily used in connection with positive displacement pumps, is measured in units such as gallons, cubic inches, and liters.

Energy the ability to do work.

1. *Potential energy*: energy due to the liquid's location or condition.
2. *Kinetic energy*: energy of motion.

Flow the volume or amount of a liquid moving through a channel or pipe. It is measured in million gallons per day (MGD), gallons per day, and cubic feet per second. In most hydraulic calculations, the flow is expressed in cubic feet per second. To obtain cubic feet per second when flow is given in million gallons per day multiply by 1.55 ft^3/sec/MGD:

$$Q\left(\mathrm{ft}^3/\mathrm{sec}\right) = \mathrm{MGD} \times 1.55\ \mathrm{ft}^3/\mathrm{sec/MGD} \qquad (7.1)$$

Head the energy a liquid possesses at a given point or that a pump must supply to move a liquid to a given location. Head is expressed in feet. Any head term can be converted to pressure by using Equation 7.2:

$$p = \rho \times h \qquad (7.2)$$

where
p = pressure, (lb/ft^2)
ρ = density (lb/ft^3)
h = head (ft)

1. *Cut-off head:* the head at which the energy supplied by a pump and the energy required to move the liquid to a specified point are equal and no discharge at the desired point will occur.
2. *Friction head*: the amount of energy in feet that is necessary to overcome the resistance of flow, which occurs in the pipes and fixtures (i.e., fittings, valves, entrances, and exits) where the liquid is flowing.
3. *Pressure head*: the vertical distance a given pressure can raise a liquid. For example, if a liquid has a pressure of 1 lb per square inch, the liquid will rise to a height of 2.31 ft.
4. *Pump head*: the energy in feet that a pump supplies to the fluid.
5. *Static head*: the energy in feet required to move a fluid from the supply tank to the discharge point (see Figure 7.3).
6. *Total head*: the total energy in feet required to move a liquid from the supply tank to the discharge point, taking into account the velocity head and the friction head (see Figure 7.4 and Figure 7.5).
7. *Velocity head*: the energy in feet required to maintain a given speed in the liquid being moved. If the pump inlet nozzle and discharge nozzle are of equal size, then this term is normally zero.

$$\text{Velocity head}\left(h_v\right) = V^2/2g \qquad (7.3)$$

where
V = liquid velocity in a pipe
G = gravity acceleration, influenced by both altitude and latitude. At sea level and 45° latitude, it is 32.17 ft/sec/sec.

8. *Suction head*: the total head in feet on the suction or supply side of the pump when the supply is loaded above the center of the pump.
9. *Discharge head*: the total head in feet on the discharge side of the pump.
10. *Suction lift*: the total head in feet on the suction or supply side of the pump when the supply is located below the center of the pump.
11. *Total differential head*: the difference between the discharge head and the suction head, expressed in feet or meters.

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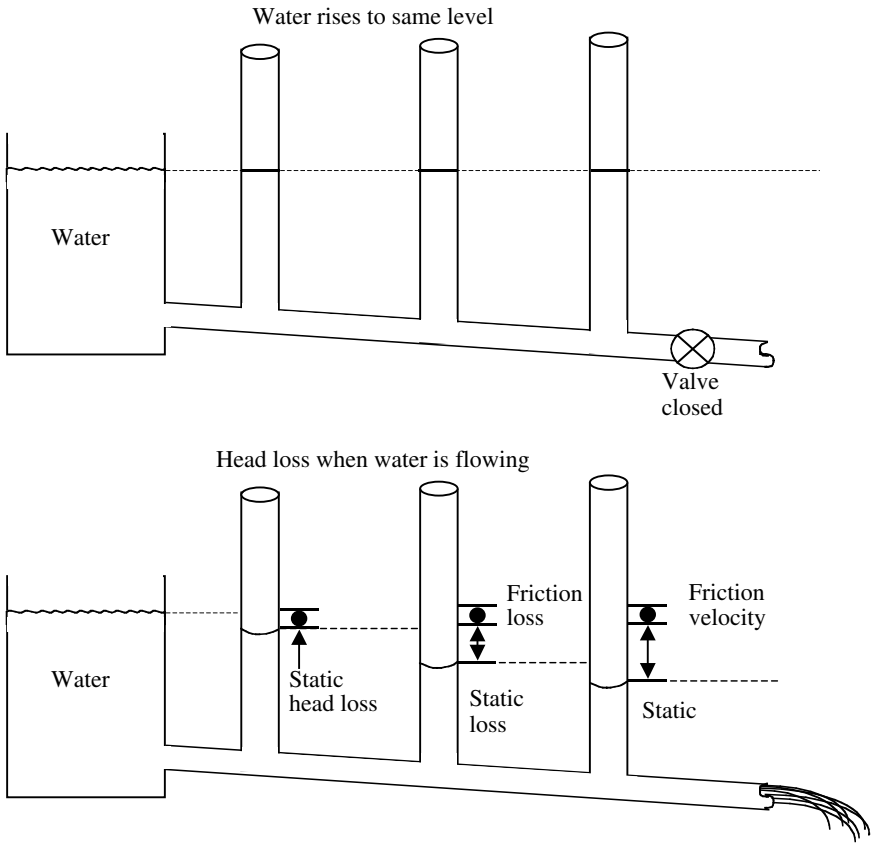

FIGURE 7.3 Head loss in non-pumping system. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Horsepower (hp) work a pump performs while moving a determined amount of liquid at a given pressure.

1. *Hydraulic (water) horsepower (Whp)*: pump output measured in whp.
2. *Brake horsepower (Bhp)*: the lowest continuous flow at which a manufacturer will guarantee a pump's performance.

Minimum flow the lowest continuous flow at which a manufacturer will guarantee a pump's performance.

Minimum flow bypass a pipe leading from the pump discharge piping back into the pump suction system. A pressure control, or flow control, valve opens this line when the pump discharge flow approaches the pump's minimum flow values. The purpose is to protect the pump from damage.

Net positive suction head (NPSH) the net positive suction head available (NPSHA) is the NPSH in feet available at the centerline of the pump inlet flange. The net positive suction head required (NPSHR) refers to the NPSH specified by a pump manufacturer for proper pump operation.

Power use of energy to perform a given amount of work in a specified length of time. In most cases, this is expressed in terms of horsepower.

Pressure a force applied to a surface. The measurements for pressure can be expressed as various functions of pounds per square inch, such as:

Atmospheric pressure (psi)	= 14.7 psi
Metric atmosphere	= psi × 0.07
Kilograms per square centimeter (kg/cm^2)	= psi × 0.07
Kilopascals	= psi × 6.89
Bars	= psi × 14.50

Pump performance curves performance curves for centrifugal pumps are different from curves drawn for positive displacement pumps. This is because the centrifugal is a dynamic device; that is, the performance of the pump responds to forces of acceleration and velocity. Note that every specific performance curve is based on a particular speed, a specific impeller diameter, impeller width, and fluid viscosity (usually taken as the viscosity of water).

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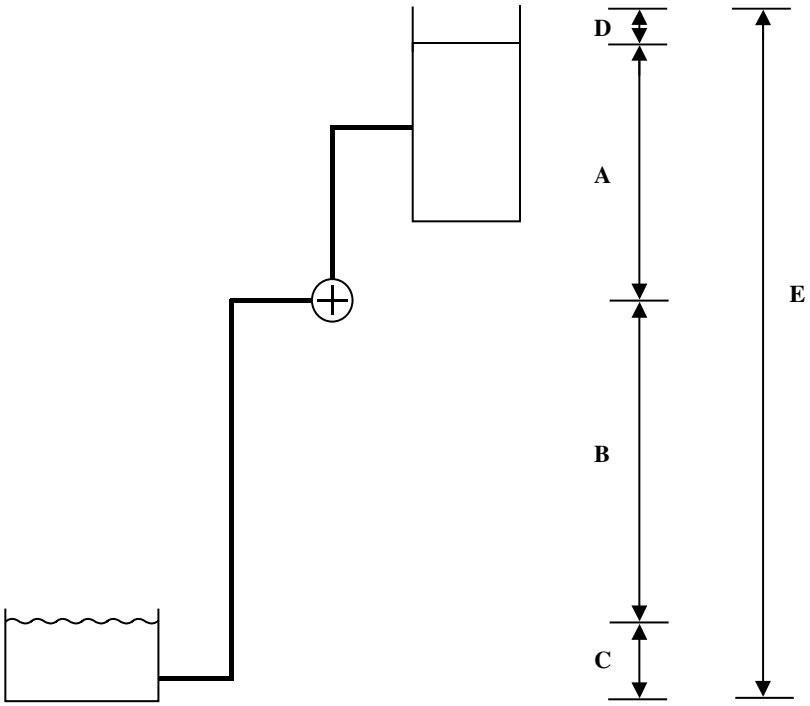
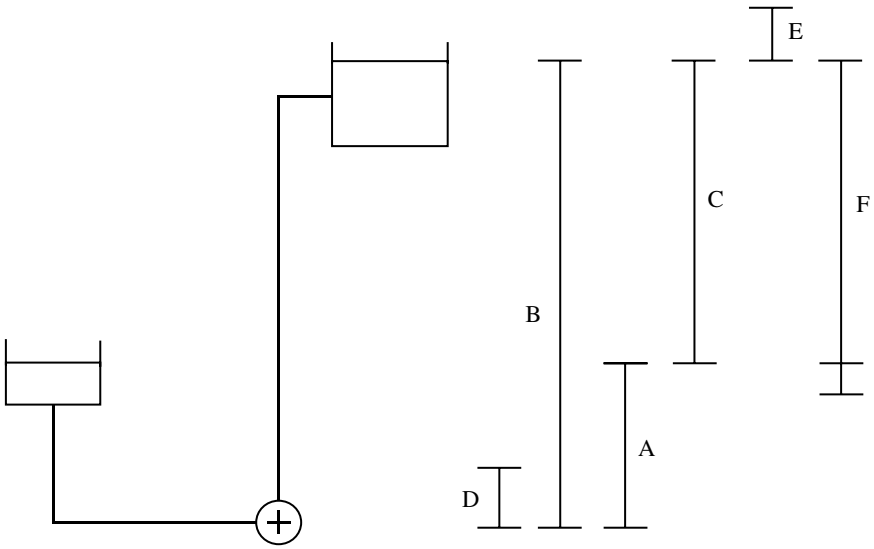


A – Static discharge head
B – Static suction lift
C – Suction friction head
D – Discharge friction head
E – Total head (A + B + C + D)

FIGURE 7.4 Head components for suction lift system. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)



A – Static suction head
B – Static discharge head
C – Static head (2 – 1)
D – Suction friction head
E – Discharge friction head
F – Total head ((1 – 2) + 3 + 4)

FIGURE 7.5 Head components for suction head type system. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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Specific Gravity (sp gr) the result of dividing the weight of an equal volume of water at 68°F. If the data is in grams per milliliter, the specific gravity of a body of water is the same as its density at 4°C.

Specific speed in the case of centrifugal pumps, a correlation of pump capacity, head, and speed at optimum efficiency is used to classify the pump impellers with respect to their specific geometry. This correlation is called specific speed, and is an important parameter for analyzing pump performance.

Suction pressure the pressure, in psig, at the suction nozzle's centerline.

The affinity laws any machine that imparts velocity and converts a velocity to pressure can be categorized by a set of relationships that apply to any dynamic conditions. These relationships are referred to as the affinity laws. They can be described as similarity processes, which follow the following rules:

1. Capacity varies as the rotating speed — the peripheral velocity of the impeller.
2. Head varies as the square of the rotating speed.
3. Brake horsepower varies as the cube of the rotating speed.

Vacuum any pressure below atmospheric pressure is a partial vacuum. The expression for vacuum is in inches of millimeters of mercury (Hg). Full vacuum is at 30 in. Hg. To convert inches to millimeters multiply inches by 25.4.

Vapor Pressure (vp) at a specific temperature and pressure, a liquid will boil. The point at which the liquid begins to boil is the liquid's vapor pressure. The vapor pressure will vary with changes in either temperature or pressure, or both.

Velocity (V) the speed of the fluid moving through a pipe or channel. It is normally expressed in feet per second.

Volumetric efficiency found by dividing a pump's actual capacity by the calculated displacement. The expression is primarily used in connection with positive displacement pumps.

Work using energy to move an object a distance. It is usually expressed in foot-pounds.

7.4 BASIC PRINCIPLES OF WATER HYDRAULICS[7]

Recall that hydraulics is defined as the study of fluids at rest and in motion. While basic principles apply to all fluids, for our purposes we consider only those principles that apply to water and wastewater. (Note: Although much of the basic information that follows is concerned with the hydraulics of distribution systems [i.e., piping, etc.], it is important for the operator to understand these basics in order to more fully appreciate the function of pumps.)

7.4.1 Weight of Air

Our study of water hydraulics begins with air. A blanket of air, many miles thick, surrounds the earth. The weight of this blanket on a given square inch of the earth's surface will vary according to the thickness of the atmospheric blanket above that point. At sea level, the pressure exerted is 14.7 psi. On a mountaintop, air pressure decreases because the blanket is not as thick.

7.4.2 Weight of Water

Because water must be stored and moving in water supplies, and wastewater must be collected, processed in unit processes, and outfalled to its receiving body, we must consider some basic relationships in the weight of water. One cubic foot of water weighs 62.4 lb and contains 7.48 gal. One cubic inch of water weighs 0.0362 lb. Water one foot deep will exert a pressure of 0.43 psi on the bottom area (12 in × 0.062 lb/in^3). A column of water two feet high exerts 0.86 psi, one 10 ft high exerts 4.3 psi, and one 52 ft high exerts:

$$52 \text{ ft} \times 0.43 \text{ psi/ft} = 22.36 \text{ psi}$$

A column of water 2.31 feet high will exert 1.0 psi. To produce a pressure of 40 psi requires a water column:

$$40 \text{ psi} \times 2.31 \text{ ft/psi} = 92.4 \text{ ft}$$

The term head is used to designate water pressure in terms of the height of a column of water in feet. For example, a 10-ft column of water exerts 4.3 psi. This can be called 4.3-psi pressure or 10 ft of head.

Another example: if the static pressure in a pipe leading from an elevated water storage tank is 37 psi, what is the elevation of the water above the pressure gauge?

Remembering that 1 psi = 2.31 and that the pressure at the gauge is 37 psi.

$$37 \text{ psi} \times 2.31 \text{ ft/psi} = 85.5 \text{ ft (rounded)}$$

7.4.3 Weight of Water Related to the Weight of Air

The theoretical atmospheric pressure at sea level (14.7 psi) will support a column of water 34 ft high:

$$14.7 \text{ psi} \times 2.31 \text{ ft/psi} = 33.957 \text{ or } 34 \text{ ft}$$

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At an elevation of 1 mi above sea level, where the atmospheric pressure is 12 psi, the column of water would be only 28 ft high (12 psi × 2.31 ft/psi = 27.72 ft or 28 ft).

If a tube is placed in a body of water at sea level (a glass, a bucket, a water storage reservoir, or a lake, pool, etc.), water still rise in the tube to the same height as the water outside the tube. The atmospheric pressure of 14.7 psi will push down equally on the water surface inside and outside the tube.

However, if the top of the tube is tightly capped and all of the air is removed from the sealed tube above the water surface, forming a perfect vacuum, the pressure on the water surface inside the tube will be zero psi. The atmospheric pressure of 14.7 psi on the outside of the tube will push the water up into the tube until the weight of the water exerts the same 14.7 psi pressure at a point in the tube even with the water surface outside the tube. The water will rise 14.7 psi × 2.31 ft/psi = 34 feet.

In practice, it is impossible to create a perfect vacuum, so the water will rise somewhat less than 34 ft; the distance it rises depends on the amount of vacuum created.

Example 7.1

Problem:

If enough air was removed from the tube to produce an air pressure of 9.7 psi above the water in the tube, how far will the water rise in the tube?

Solution:

To maintain the 14.7-psi at the outside water surface level, the water in the tube must produce a pressure of 5 psi (14.7 psi × 9.7 psi = 5.0 psi). The height of the column of water that will produce 5.0 psi is:

$$5.0 \text{ psi} \times 2.31 \text{ ft/psi} = 11.5 \text{ ft (rounded)}$$

7.4.4 Water at Rest

As mentioned in Chapter 5, Steven's law states, "The pressure at any point in a fluid at rest depends on the distance measured vertically to the free surface and the density of the fluid." Stated as a formula, this becomes:

$$p = w \times h \tag{7.4}$$

where

p = pressure (lb/ft^2)
w = density (lb/ft^3)
h = vertical distance (ft)

Example 7.2

Problem:

What is the pressure at a point 15 ft below the surface of a reservoir?

Solution:

To calculate this, we must know that the density of water, w, is 62.4 lb/ft^3. Thus:

$$p = w \times h$$

$$= 62.4 \text{ lb/ft}^3 \times 15 \text{ ft}$$

$$= 936 \text{ lb/ft}^2$$

Waterworks and wastewater operators generally measure pressure in pounds per square inch rather than pounds per square foot; to convert, divide by 144 in.^{2}ft^2 (12 in. × 12 in. = 144 in.^{2}):

$$p = \frac{936 \text{ lb/ft}^2}{144 \text{ in.}^2/\text{ft}^2} = 6.5 \text{ psi}$$

7.4.5 Gauge Pressure

We defined head as the height a column of water would rise due to the pressure at its base. We demonstrated that a perfect vacuum plus atmospheric pressure of 14.7 psi would lift the water 34 ft. If we now open the top of the sealed tube to the atmosphere and enclose the reservoir, and then increase the pressure in the reservoir, the water will again rise in the tube. Because atmospheric pressure is essentially universal, we usually ignore the first 14.7-psi of actual pressure measurements and measure only the difference between the water pressure and the atmospheric pressure; we call this gauge pressure.

Example 7.3

Problem:

Water in an open reservoir is subjected to the 14.7 psi of atmospheric pressure, but subtracting this 14.7 psi leaves a gauge pressure of 0 psi. This shows that the water would rise 0 ft above the reservoir surface. If the gauge pressure in a water main is 100 psi, how far would the water rise in a tube connected to the main?

Solution:

$$100 \text{ psi} \times 2.31 \text{ ft/psi} = 231 \text{ ft}$$

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7.4.6 Water in Motion

The study of water flow is much more complicated than that of water at rest. It is important to have an understanding of these principles because the water or wastewater in a treatment plant and distribution or collection system is nearly always in motion (much of this motion is the result of pumping).

7.4.6.1 Discharge

Discharge is the quantity of water passing a given point in a pipe or channel during a given period. It can be calculated by the formula:

$$Q = V \times A \tag{7.5}$$

where

Q = discharge (ft^3/sec)
V = water velocity (ft/sec)
A = cross-section area of the pipe or channel (ft^2)

The discharge can be converted from cubic feet per second to other units, such as gallons per minute or million gallons per day, by using appropriate conversion factors.

Example 7.4

Problem:

A pipe 12 in. in diameter has water flowing through it at 10 ft/sec. What is the discharge in (a) cubic feet per second, (b) gallons per minute, and (c) million gallons per day?

Solution:

Before we can use the basic formula, we must determine the area (A) of the pipe. The formula for the area is:

$$A = \pi \times \frac{D^2}{4} = \pi \times r^2$$

where

D = diameter of the circle in feet
r = radius of the circle in feet
π = the constant value 3.14159

So, the area of the pipe is:

$$A = \pi \times \frac{D^2}{4} = 3.14159 = 0.785 \text{ ft}^2$$

Now, we can determine the discharge in cubic feet per second (part [a}):

$$Q = V \times A$$
$$= 10 \text{ ft/sec} \times 0.785 \text{ ft}^2$$
$$= 7.85 \text{ ft}^3/\text{sec or ft}^3/\text{sec}$$

For part (b), we need to know that 1 ft^3/sec is 449 gallons per minute, so 7.85 ft^3/sec × 449 gal/min/ft^3/sec = 3520 gal/min.

Finally, for part (c), 1 MGD is 1.55 ft^3/sec, so:

$$\frac{7.85 \text{ ft}^3/\text{sec}}{1.55 \text{ ft}^3/\text{sec/MGD}} = 5.06 \text{ MGD}$$

7.4.6.2 The Law of Continuity

The law of continuity states that the discharge at each point in a pipe or channel is the same as the discharge at any other point (provided water does not leave or enter the pipe or channel). In equation form, this becomes:

$$Q_1 = Q_2 \text{ or } A_1 \times V_1 = A_2 \times V_2 \tag{7.6}$$

Example 7.5

Problem:

A pipe 12 inches in diameter is connected to a 6-inch diameter pipe. The velocity of the water in the 12-inch pipe is 3 fps. What is the velocity in the 6-in. pipe?

Solution:

Using the equation $A_1 \times V_1 = A_2 \times V_2$, we need to determine the area of each pipe:

$$\text{12 in. pipe: } A = \Pi \times \frac{D^2}{4}$$
$$= 3.14159 \times \frac{(1 \text{ ft})^2}{4}$$
$$= 0.785 \text{ ft}^2$$

$$\text{6 in. pipe: } A = 3.14159 \times \frac{(0.5)^2}{4}$$
$$= 0.196 \text{ ft}^2$$

The continuity equation now becomes

$$0.785 \text{ ft}^2 \times 3 \text{ ft/sec} = 0.196 \text{ ft}^2 \times V_2$$

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Solving for V_2:

$$V_2 = \frac{0.785\ \text{ft}^2 \times 3\ \text{ft/sec}}{0.196\ \text{ft}^2}$$

$$= 12\ \text{ft/sec}$$

7.4.7 Pipe Friction

The flow of water in pipes is caused by the pressure applied behind it either by gravity or by hydraulic machines (pumps). The flow is retarded by the friction of the water against the inside of the pipe. The resistance of flow offered by this friction depends on the size (diameter) of the pipe, the roughness of the pipe wall, and the number and type of fittings (bends, valves, etc.) along the pipe. It also depends on the speed of the water through the pipe — the more water you try to pump through a pipe, the more pressure it will take to overcome the friction. The resistance can be expressed in terms of the additional pressure needed to push the water through the pipe, in either pounds per square inch or feet of head. Because it is a reduction in pressure, it is often referred to as friction loss or head loss.

Friction loss increases as:

1. Flow rate increases
2. Pipe diameter decreases
3. Pipe interior becomes rougher
4. Pipe length increases
5. Pipe is constricted
6. Bends, fittings, and valves are added

The actual calculation of friction loss is beyond the scope of this text. Many published tables give the friction loss in different types and diameters of pipe and standard fittings. What is more important here is recognition of the loss of pressure or head due to the friction of water flowing through a pipe.

One of the factors in friction loss is the roughness of the pipe wall. As mentioned, a number called the C factor indicates pipe wall roughness; the higher the C factor, the smoother the pipe.

Note: C factor is derived from the letter C in the Hazen-Williams equation for calculating water flow through a pipe.

Some of the roughness in the pipe will be due to the material; cast iron pipe will be rougher than plastic, for example. Additionally, the roughness will increase with corrosion of the pipe material and deposit sediments in the pipe. New water pipes should have a C factor of 100 or more; older pipes can have C factors that are lower.

In determining C factor, published tables are usually used. In addition, when the friction losses for fittings are factored in, other published tables are available to make the proper determinations. It is standard practice to calculate the head loss from fittings by substituting the *equivalent length of pipe,* which is also available from published tables.

7.5 BASIC PUMPING CALCULATIONS[8]

Certain computations used for determining various pumping parameters are important to water and wastewater operators.

7.5.1 Pumping Rates

Note: The rate of flow produced by a pump is expressed as the volume of water pumped during a given period.

The mathematical problems most often encountered by water and wastewater operators in regards to determining pumping rates are often determined by using Equations 7.7 or Equation 7.8.

$$\text{Pumping Rate}\ (\text{gal/min}) = \frac{\text{Gallons}}{\text{Minutes}} \tag{7.7}$$

$$\text{Pumping Rate}\ (\text{gal/h}) = \frac{\text{Gallons}}{\text{Hours}} \tag{7.8}$$

Example 7.6

Problem:

The meter on the discharge side of the pump reads in hundreds of gallons. If the meter shows a reading of 110 at 2:00 P.M. and 320 at 2:30 P.M., what is the pumping rate expressed in gallons per minute?

Solution:

The problem asks for pumping rate in gallons per minute, so we use Equation 7.7.

Step 1: To solve this problem, we must first find the total gallons pumped (determined from the meter readings):

32,000 gal – 11,000 gal = 21,000 gal

Step 2: The volume was pumped between 2:00 P.M. and 2:30 P.M., for a total of 30 min. From this information, calculate the gallons-per-minute pumping rate.

$$\text{Pumping Rate}\ (\text{gal/min}) = \frac{21{,}000\ \text{gal}}{30\ \text{min}}$$

$$= 700\ \text{gal/min}\ \text{pumping rate}$$

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Example 7.7

Problem:

During a 15-min pumping test, 16,400 gal were pumped into an empty rectangular tank. What is the pumping rate in gallons per minute?

Solution:

The problem asks for the pumping rate in gallons per minute, so again we use

$$\text{Pumping Rate (gal/min)} = \frac{\text{Gallons}}{\text{Minutes}} = \frac{16{,}400 \text{ gal}}{15 \text{ min}} = 1{,}033 \text{ gal/min pumping rate (rounded)}$$

Example 7.8

Problem:

A tank 50 ft in diameter is filled with water to depth of 4 ft. To conduct a pumping test, the outlet valve to the tank is closed, and the pump is allowed to discharge into the tank. After 80 min, the water level is 5.5 ft. What is the pumping rate in gallons per minute?

Solution:

Step 1: We must first determine the volume pumped in cubic feet:

$$\text{Volume Pumped} = \text{Area of circle} \times \text{Depth} = 0.785 \times 50 \text{ ft} \times 50 \text{ ft} \times 1.5 \text{ ft} = 2944 \text{ ft}^3 \text{ (rounded)}$$

Step 2: Convert the cubic-feet volume to gallons:

$$3944 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 22{,}021 \text{ gal (rounded)}$$

Step 3: The pumping test was conducted over a period of 80 min. Using Equation 7.7, calculate the pumping rate in gallons per minute.

$$\text{Pumping Rate (gal/min)} = \frac{\text{Gallons}}{\text{Minutes}} = \frac{21{,}021 \text{ gal}}{80 \text{ min}} = 275.3 \text{ gal/min (rounded)}$$

7.5.2 Calculating Head Loss

Note: Pump head measurements are used to determine the amount of energy a pump can or must impart to the water; they are measured in feet.

One of the principle calculations used in pumping problems is determining *head loss.* The following formula is used to calculate head loss:

$$H_f = K\left(V^2/2g\right) \tag{7.9}$$

where

H_f = friction head
K = friction coefficient
V = velocity in pipe
G = gravity (32.17 ft/sec/sec)

7.5.3 Calculating Head

For centrifugal pumps and positive displacement pumps, several other important formulae are used in determining head. In centrifugal pump calculations, the conversion of the discharge pressure to discharge head is the norm. Positive displacement pump calculations often leave given pressures in pounds per square inch.

In the following formulae, W expresses the specific weight of liquid in pound per cubic foot. For water at 68°F, W is 62.4 lb/ft.^{3} A water column 2.31 ft high exerts a pressure of 1 psi on 64°F water. Use the following formulae to convert discharge pressure in psig to head in feet:

1. Centrifugal pumps:

$$H\,(\text{ft}) = \frac{p\,(\text{psig}) \times 2.31}{\text{sp gr}} \tag{7.10}$$

2. Positive displacement pumps

$$H\,(\text{ft}) = \frac{p\,(\text{psig}) \times 144}{W} \tag{7.11}$$

To convert head into pressure:

1. Centrifugal pumps

$$p\,(\text{psi}) = \frac{H\,(\text{ft}) \times \text{sp gr}}{2.31} \tag{7.12}$$

2. Positive displacement pumps

$$p\,(\text{psi}) = \frac{H\,(\text{ft}) \times W}{W} \tag{7.13}$$

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7.5.4 Calculating Horsepower and Efficiency

When considering work being done, we consider the rate at which work is being done. This is called power and is labeled as foot-pounds per second. At some point in the past, it was determined that the ideal work animal, the horse, could move 550 lb 1 ft, in 1 sec. Because large amounts of work are also to be considered, this unit became known as horsepower.

When pushing a certain amount of water at a given pressure, the pump performs work. One horsepower equals 33,000 ft-lb/min. The two basic terms for horsepower are: (1) Hydraulic horsepower (Whp) and (2) brake horsepower (Bhp).

7.5.4.1 Hydraulic Horsepower

One hydraulic horsepower equals the following:

1. 550 ft-lb/sec
2. 33,000 ft-lb/min
3. 2,545 Btu/hr
4. 0.746 kW
5. 1014 metric hp

To calculate the hydraulic horsepower using flow in gallons per minute and head in feet, use the following formula for centrifugal pumps:

$$\text{Whp} = \frac{Q\,(\text{gal/min}) \times \text{Head (ft)} \times \text{sp gr}}{3960} \tag{7.14}$$

When calculating horsepower for positive displacement pumps, common practice is to use pounds per square inch for pressure. Then the hydraulic horsepower becomes:

$$\text{Whp} = \frac{Q\,(\text{gal/min}) \times p\,(\text{psi})}{3960} \tag{7.15}$$

7.5.4.2 Pump Efficiency and Brake Horsepower

When a motor-pump combination is used (for any purpose), neither the pump nor the motor will be 100% efficient. Simply, not all the power supplied by the motor to the pump (called brake horsepower) will be used to lift the water (water or hydraulic horsepower); some of the power is used to overcome friction within the pump.

Similarly, not all of the power of the electric current driving the motor (called *motor horsepower,* mhp) will be used to drive the pump. Some of the current is used to overcome friction within the motor, and some current is lost in the conversion of electrical energy to mechanical power.

Note: Depending on size and type, pumps are usually 50 to 85% efficient, and motors are usually 80 to 95% efficient. The efficiency of a particular motor or pump is given in the manufacturer's technical manual accompanying the unit.

A pump's brake horsepower equals its hydraulic horsepower divided by the pump's efficiency. Thus, the brake horsepower formulas become:

$$\text{Bhp} = \frac{Q\,(\text{gal/min}) \times \text{Head (ft)} \times \text{sp gr}}{3960 \times \text{Efficiency}} \tag{7.16}$$

or

$$\text{Bhp} = \frac{Q\,(\text{gal/min}) \times p\,(\text{psig})}{1714 \times \text{Efficiency}} \tag{7.17}$$

Example 7.9

Problem:

Calculate the brake horsepower requirements for a pump handling salt water and having a flow of 600 gal/min with 40-psi differential pressure. The specific gravity of salt water at 68°F equals 1.03. The pump efficiency is 85%.

Solution:

Convert the pressure differential to total differential head (TDH):

$$\text{TDH} = 40 \times 2.31/1.03 = 90 \text{ ft (rounded)}$$

$$\text{Bhp} = \frac{600 \times 90 \times 1.03}{3960 \times 0.85}$$

$$= 16.5 \text{ hp (rounded)}$$

or

$$\text{Bhp} = \frac{600 \times 40}{1714 \times 0.85}$$

$$= 16.5 \text{ hp (rounded)}$$

Note: Horsepower requirements vary with flow. Generally, if the flow is greater, the horsepower required moving the water would be greater.

When the motor, brake, and motor horsepower are known and the efficiency is unknown, a calculation to determine motor or pump efficiency must be done. Equation 7.18 is used to determine percent efficiency:

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$$\text{Percent Efficiency} = \frac{\text{hp Output}}{\text{hp Input}} \times 100 \quad (7.18)$$

From Equation 7.18, the specific equations to be used for motor, pump, and overall efficiency equations are

$$\text{Percent Motor Efficiency} = \frac{\text{Bhp}}{\text{Mhp}} \times 100 \quad (7.19)$$

$$\text{Percent Pump Efficiency} = \frac{\text{Whp}}{\text{Bhp}} \times 100 \quad (7.20)$$

$$\text{Percent Overall Efficiency} = \frac{\text{Whp}}{\text{Mhp}} \quad (7.21)$$

Example 7.10

Problem:

A pump has a water horsepower requirement of 8.5 Whp. If the motor supplies the pump with 12 hp, what is the efficiency of the pump?

Solution:

$$\begin{aligned}\text{Percent Pump Efficiency} &= \frac{\text{Whp Output}}{\text{Bhp Supplied}} \times 100 \\ &= \frac{8.5\ \text{Whp}}{12\ \text{Bhp}} \times 100 \\ &= 0.71 \times 100 \\ &= 71\%\ \text{(rounded)}\end{aligned}$$

Example 7.11

Problem:

What is the efficiency if an electric power equivalent to 25-hp is supplied to the motor and 14-hp of work is accomplished by the pump?

Solution:

Calculate the percent of overall efficiency:

$$\begin{aligned}\text{Percent Overall Efficiency} &= \frac{\text{hp Output}}{\text{hp Supplied}} \times 100 \\ &= \frac{14\ \text{Whp}}{25\ \text{Bhp}} \times 100 \\ &= 0.56 \times 100 \\ &= 56\%\end{aligned}$$

Example 7.12

Problem:

Approximately 12 kW of power is supplied to the motor. If the brake horsepower is 14 Bhp, what is the efficiency of the motor?

Solution:

First, convert the kilowatt power to horsepower. Based on the fact that 1 hp = 0.746 kW, the equation becomes:

$$\frac{12\ \text{kW}}{0.746\ \text{kW/hp}} = 16.09\ \text{hp}$$

Now calculate the percent efficiency of the motor:

$$\begin{aligned}\text{Percent Motor Efficiency} &= \frac{\text{hp Output}}{\text{hp Supplied}} \times 100 \\ &= \frac{14\ \text{Whp}}{16.09\ \text{Mhp}} \times 100 \\ &= 0.87 \times 100 \\ &= 87\%\end{aligned}$$

7.5.5 Specific Speed

Specific speed (N_s) refers to an impeller's speed when pumping 1 gal/min of liquid at a differential head of 1 ft. Use the following equation for specific speed, where H is at the best efficiency point:

$$N_s = \frac{\text{rpm} \times Q^{0.5}}{H^{0.75}} \quad (7.22)$$

where
rpm = revolutions per minute
Q = flow (gal/min)
H = head (ft)

Pump-specific speeds vary between pumps. No absolute rule sets the specific speed for different kinds of centrifugal pumps. However, the following N_s ranges are quite common.

Pump	N_s Range
Volute, diffuser, and vertical turbine	500–5000
Mixed flow	5000–10,000
Propeller	9000–15,000

Note: The higher the specific speed of the pump, the higher the efficiency.

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7.6 PUMP CHARACTERISTIC CURVES

The interrelations of pump head, flow, efficiency and horsepower are known as the characteristics of the pump. These are important elements in pump performance, and they are diagrammed graphically on a performance curve. The characteristics commonly shown on a pump curve are:

1. Capacity (flow rate)
2. Total head
3. Power (brake horsepower)
4. Efficiency
5. Speed (Note: Speed is only a characteristic if the pump is driven by a variable-speed motor. For our purposes, we will assume that the pump is driven by a constant-speed motor, so the graphs used have only four curves.)

Note: The four pump characteristics that we are concerned with here (capacity, head, power, and efficiency) are related to each other. This is an extremely important point as it is this interrelationship that enables the four pump curves to be plotted on the same graph.

Experience has shown some important relationships between capacity, head, power, and efficiency:

1. The capacity (flow rate) of a pump changes as the head against which the pump is working changes.
2. Pump capacity also changes as the power supplied to the pump changes.
3. Pump capacity changes as efficiency changes.

Consequently, head, power, and efficiency can all be graphed as a function of pump capacity. That is, capacity, Q (designated in gallons per minute or cubic meters per second), is shown along the horizontal (bottom — the x-axis) scale of the graph. Head (in pounds per square inch, feet of water, or other pressure designations), power, and efficiency (any one or a combination of them) are shown along the vertical (side — the y-axis) scale of the graph.

Note: Performance curves for centrifugal pumps are different in kind from curves drawn for positive displacement pumps. This is the case because the centrifugal pump is a dynamic device, in that the performance of the pump responds to forces of acceleration and velocity.

7.6.1 Head-Capacity Curve

Head-capacity (H-Q) is the curve indicating the relationship between total head, H, and pressure, against which the pump must operate and pump capacity Q. Figure 7.6 shows a typical H-Q curve. The curve indicates what flow rate the pump will produce at any given total head.

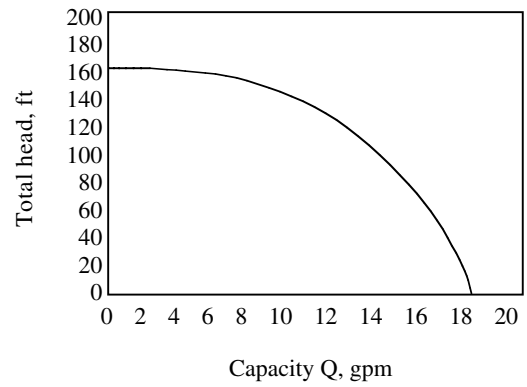

FIGURE 7.6 H-Q curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

The curve for a centrifugal pump may slope to the left, to the right, or may be a flattish curve, depending on the specific speed of the impeller. As capacity increases, the total head that the pump is capable of developing is reduced.

As shown in Figure 7.6, the capacity of the pump decreases as the total head increases (i.e., when the force against which the pump must work increases, the flow rate decreases). The way total head controls the capacity is a characteristic of a particular pump.

Note: For pumps, except those having a flattish curve, the highest head occurs at the point where there is no flow through the pump; that is, when the pump is running with the discharge valve closed.

7.6.2 The Power-Capacity Curve

The power-capacity (P-Q) curve (Figure 7.7) shows the relationship between power P and capacity Q. In this figure, pump capacity is measured as gallons per minute, and power is measured as brake horsepower.

Note: Knowledge of what power the pump requires is valuable for checking the adequacy of an existing pump and motor system.

7.6.3 The Efficiency-Capacity (E-Q) Curve

The efficiency-capacity (E-Q) curve (Figure 7.8) shows the relationship between pump efficiency E and capacity Q. In sizing a pump system, the design engineer attempts to select a pump that will produce the desired flow rate at or near peak pump efficiency.

Note: The more efficient the pump, the less costly it is to operate.

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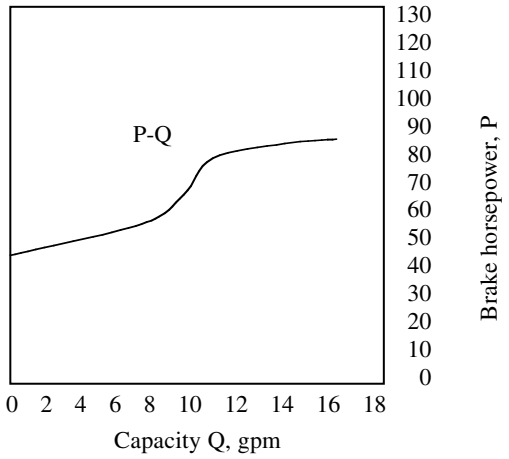

FIGURE 7.7 P-Q curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

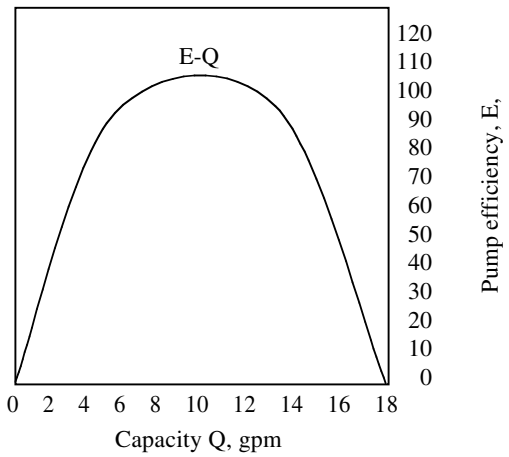

FIGURE 7.8 E-Q curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.7 PUMPS IN SERIES AND PARALLEL

Series pump operation is achieved by having one pump discharge into the suction of the next. This arrangement is used primarily to increase the discharge head (i.e., when system heads are too great for one pump to overcome), although a small increase in capacity also results.

Parallel operation is obtained by having two pumps discharging into a common header. Parallel operation is typically employed when head is insufficient, but more flow is needed. Pumps arranged in parallel increase the flow, but the head remains that of one pump working.

Series or parallel operations allow the operator to be flexible enough in pumping capacities and heads to meet requirements of system changes and extensions. With two pumps in parallel, one can be shut down during low demand. This allows the remaining pump to operate close to its optimum efficiency point.

7.8 CONSIDERATIONS FOR PUMPING WASTEWATER[9]

In pumping water, the primary consideration is to ensure that the pumping equipment is operating properly, supply service is readily available, and the pumping equipment is well maintained.

In pumping wastewater, many of the considerations are the same as with pumping water. However, the primary consideration in pumping wastewater is the pump's tendency to clog. Centrifugal pumps for wastewater (i.e., water with large solids) should always be of the single-suction type with nonclog, open impellers. (Note: Double suction pumps are prone to clogging because rags will catch and wrap around the shaft that extends through the impeller eye.) A typical simplified wastewater pump configuration is shown in Figure 7.9. Limiting the number of impeller vanes to two or three, providing for large passageways, and using a bar screen ahead of the pump can further reduce clogging.

The number of pumps used in a wastewater installation is largely dependent on expected demand, pump capacity, and design criteria for backup operation. The number of pumps and their capacities should be able to handle the peak flow with one pump in the set that is out of service.

7.9 TYPES OF PUMPS USED IN WATER AND WASTEWATER TREATMENT

According to the Hydraulic Institute, all pumps may be classified as kinetic energy pumps or positive displacement pumps.[10] Table 7.2 provides a brief description and application of many types of pumps in these two classes. Basic configurations of many types of pumps are also shown in Figure 7.10 through Figure 7.16.

7.10 INTRODUCTION TO CENTRIFUGAL PUMPS

> Fire makes things hot and bright and uses them up. Air makes things cool and sneaks in everywhere. Earth makes things solid and sturdy, so they'll last. But water, it tears things down, it falls from the sky and carries off everything it can, carries it off and down to the sea. If the water had its way, the whole world would be smooth, just a big ocean with nothing out of the water's reach. All dead and small.[12] [Thus, there would be no need for pumps.].

The centrifugal pump and its modifications are the most widely used type of pumping equipment in the water and

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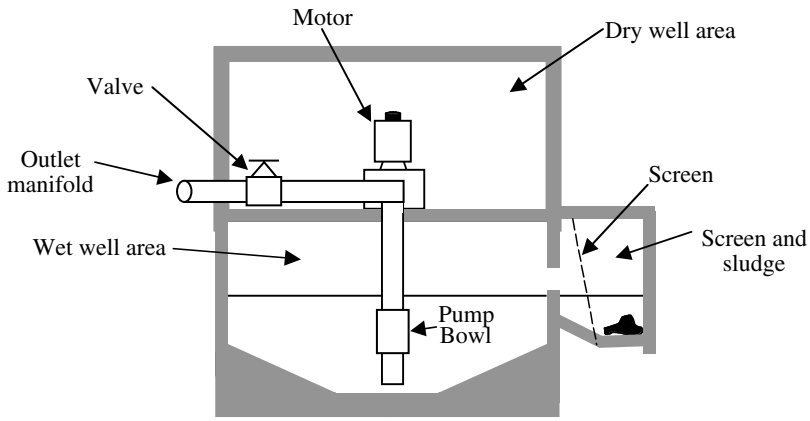

FIGURE 7.9 Simplified wastewater pump installation. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

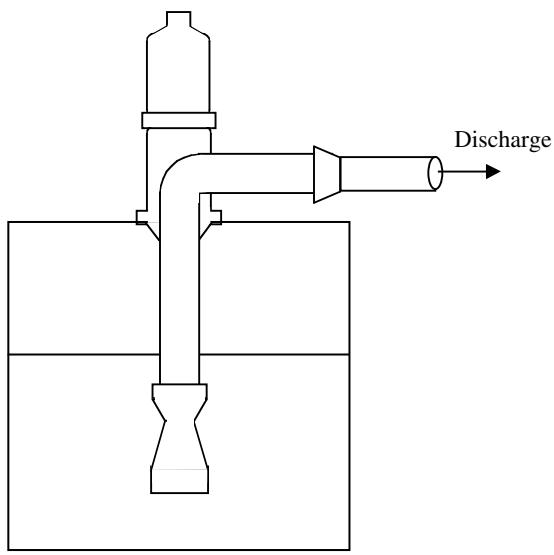

FIGURE 7.10 Wet-well suspended pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

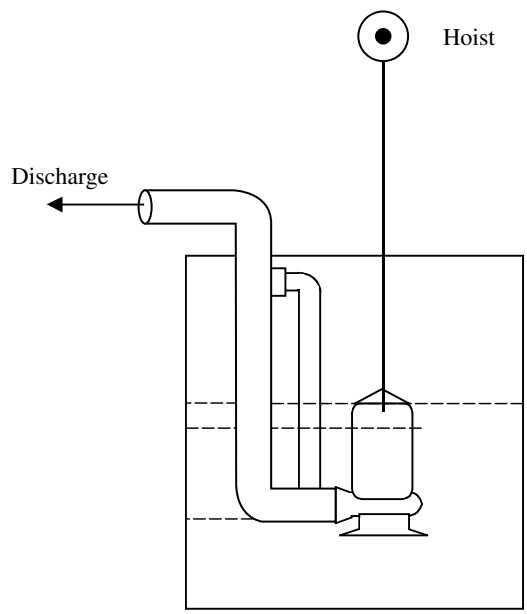

FIGURE 7.11 Wet-well submersible pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

wastewater industries. Pumps of this type are capable of moving high volumes of water in a relatively efficient manner. The centrifugal pump is very dependable, has relatively low maintenance requirements, and can be constructed out of a wide variety of construction materials. The centrifugal pump is available in a wide range of sizes, with capacities ranging from a few gallons per minute up to several thousand pounds per cubic inch.[13] It is considered one of the most dependable systems available for water and wastewater liquid transfer.

The general characteristics of the centrifugal pump are listed in Table 7.3.

In this section we will accomplish the following:

1. Describe the centrifugal pump.
2. Provide a brief discussion of pump theory.
3. Describe the types of centrifugal pumps.
4. Discuss pump characteristics.
5. Describe the advantages and disadvantages of the centrifugal pump.
6. List centrifugal pump applications.

7.10.1 Description

The centrifugal pump consists of a rotating element (impeller) sealed in a casing (volute). The rotating element is

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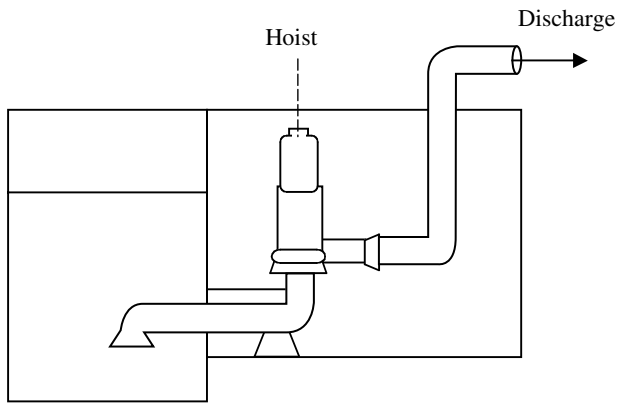

FIGURE 7.12 Dry-well centrifugal pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

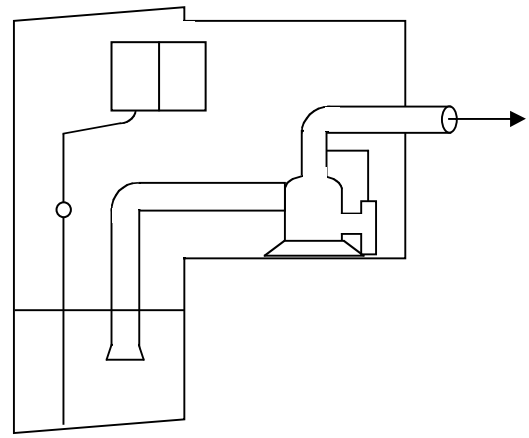

FIGURE 7.13 Dry-well self-priming pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

connected to a drive unit or prime mover (motor or engine) that supplies the energy to spin the rotating element. As the impeller spins inside the volute casing, an area of low pressure is created in the center of the impeller. This pressure allows the atmospheric pressure on the water in the supply tank to force the water up to the impeller. (Note: We use the term water to include both freshwater (potable) and wastewater, unless otherwise specified.) Because the pump will not operate if there is no low-pressure zone created at the center of the impeller, it is important that the casing be sealed to prevent air from entering the casing. To ensure the casing is airtight, the pump includes some type of seal (mechanical or conventional packing) assembly at the point where the shaft enters the casing. This seal also includes some type of lubrication (water, grease, or oil) to prevent excessive wear.

When the water enters the casing, the spinning action of the impeller transfers energy to the water. This energy is transferred to the water in the form of increased speed or velocity. The water is thrown outward by the impeller into the volute casing where the design of the casing allows the velocity of the water to be reduced, which, in turn, converts the velocity energy (velocity head) to pressure energy (pressure head). The water then travels out of the pump through the pump discharge. The major components of the centrifugal pump are shown in Figure 7.17.

7.10.2 Theory

The volute-cased centrifugal pump provides the pumping action necessary (i.e., converts velocity energy to pressure

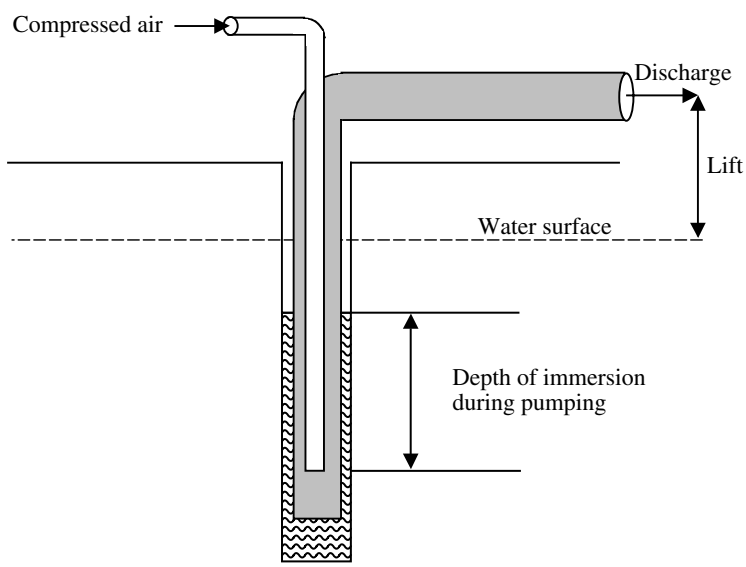

FIGURE 7.14 Air-lift pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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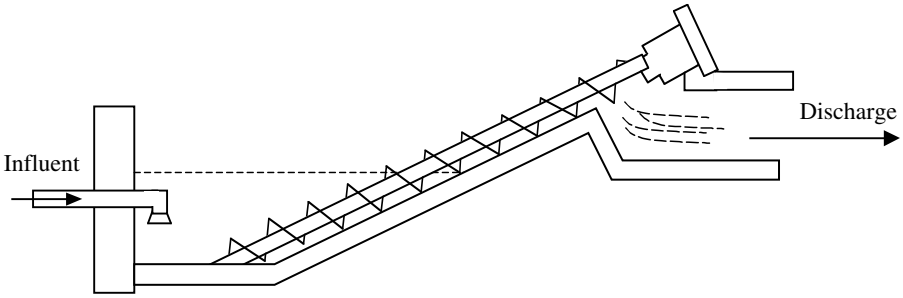

FIGURE 7.15 Screw pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

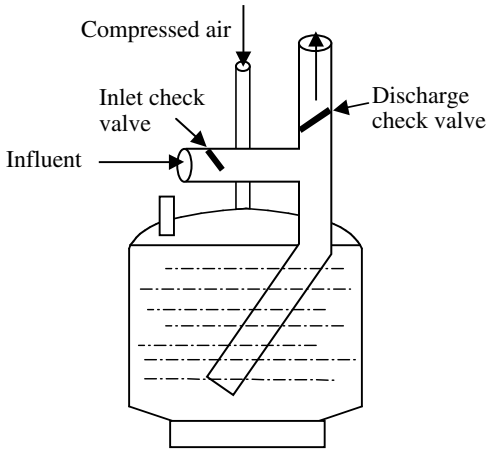

FIGURE 7.16 Pneumatic ejector. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

TABLE 7.2
Pump Types and Major Applications in Water and Wastewater[11]

Major Classification	Pump Type	Major Pumping Applications
Kinetic	Centrifugal	Raw water and wastewater, secondary sludge return and wasting, settled primary and thickened sludge, effluent
	Peripheral	Scum, grit, sludge and raw water and wastewater
	Rotary	Lubricating oils, gas engines, chemical solutions, small flows of water and wastewater
Positive Displacement	Screw	Grit, settled primary and secondary sludges, thickened sludge, raw wastewater
	Diaphragm	Chemical solution
	Plunger	Scum and primary, secondary, and settled sludges; chemical solutions
	Airlift	Secondary sludge circulation and wasting, grit
	Pneumatic ejector	Raw wastewater at small installation (100 to 600 L/min)

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

energy) to transfer water from one point to another (see Figure 7.18). The rotation of a series of vanes in an impeller creates pressure. The motion of the impeller forms a partial vacuum at the suction end of the impeller. Outside forces, such as the atmospheric pressure or the weight of a column of liquids, push water into the impeller eye and out the to the periphery of the impeller. From there, the rotation of the high-speed impeller throws the water into the pump casing. As a given volume of water moves from one cross-sectional area to another within the casing, the velocity or speed of the liquid changes proportionately.

The volute casing has a cross-sectional area that is extremely small at the point in the case that is farthest from the discharge (see Figure 7.19). This area increases

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TABLE 7.3
Characteristics of Centrifugal Pumps[14]

Characteristic	Description	Characteristic	Description
Flow rate	High	Self-priming	No
Pressure rise per stage	Low	Outlet stream	Steady
Constant variable over operating range	Pressure rise	Works with high-viscosity fluids	No

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

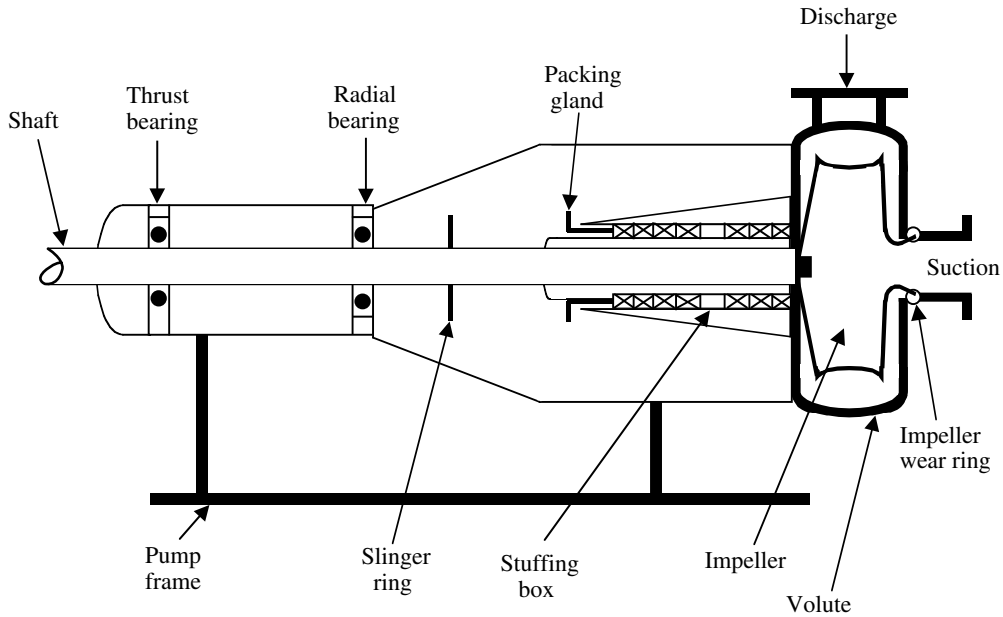

FIGURE 7.17 Centrifugal pump — major components. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

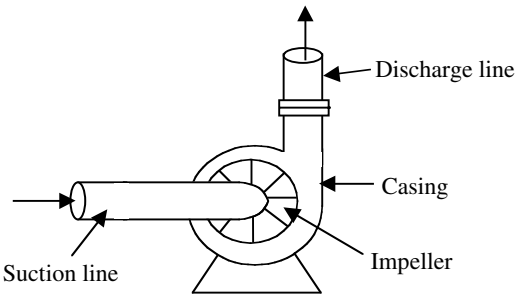

FIGURE 7.18 A centrifugal pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

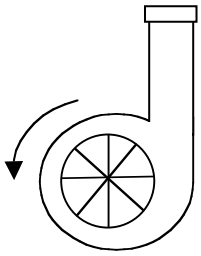

FIGURE 7.19 Centrifugal pump volute casing. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

continuously to the discharge. As this area increases, the velocity of the water passing through it decreases as it moves around the volute casing to the discharge point.

As the velocity of the liquid decreases, the velocity head decreases and the energy is converted to pressure head. There is a direct relationship between the velocity of the liquid and the pressure it exerts. As the velocity of the liquid decreases, the excess energy is converted to additional pressure (pressure head). This pressure head supplies the energy to move the liquid through the discharge piping.

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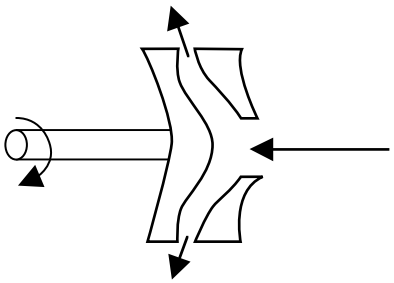

FIGURE 7.20 Centrifugal (radial) flow pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Note: A centrifugal pump will, in theory, develop the same head regardless of the fluid pumped. However, the pressure generated differs (i.e., because of specific gravity differences between various liquids).

7.10.3 Types of Centrifugal Pumps

Centrifugal pumps can be classified into three general categories according to the way the impeller imparts energy to the fluid. Each of these categories has a range of specific speeds and appropriate applications.

The three main categories of centrifugal pumps:

1. Radial flow impellers
2. Mixed flow impellers
3. Axial flow impellers

Any of these pumps can have one or several impellers, which may be:

1. Open
2. Closed
3. Semi-open
4. Single suction
5. Double suction

7.10.3.1 Radial Flow Impeller Pumps

Most centrifugal pumps are of radial flow. Radial flow impellers impart energy primarily by centrifugal force. Water enters the impeller at the hub and flows radially to the periphery (outside of the casing — see Figure 7.20). Flow leaves the impeller at a 90-degree angle from the direction it enters the pump. Single suction impellers have a specific speed less than 5000. Double suction impellers have a specific speed less than 6000.

There are several types of radial flow impeller pumps:

1. End suction pumps
2. In-line pumps

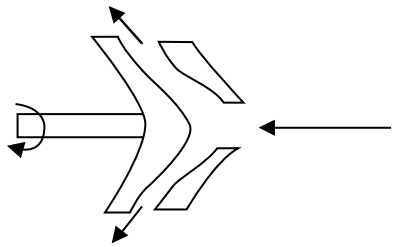

FIGURE 7.21 Mixed flow pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

3. Vertical volute pumps (cantilever)
4. Axially (horizontally) split pumps
5. Multistage centrifuge pumps
6. Vertical turbine pumps

Note: The high service pump at a potable water treatment plant that lifts water from the plant to elevated storage is usually a radial pump.

7.10.3.2 Mixed Flow Impeller Pumps

Mixed flow impellers impart energy partially by centrifugal force and partially by axial force, since the vanes act partially as an axial compressor. This type of pump has a single inlet impeller with the flow entering axially and discharging in an axial and radial direction (see Figure 7.21). Specific speeds of mixed flow pumps range from 4200 to 9000.

Note: Mixed flow impeller pumps are suitable for pumping untreated wastewater and stormwater. They operate at higher speeds than the radial-flow impeller pumps; are usually of lighter construction; and, where applicable, cost less than corresponding non-clog pumps. Impellers may be either open or enclosed, but enclosed is preferred.[15]

7.10.3.3 Axial Flow Impeller Pumps (Propeller Pump)

Axial flow impellers impart energy to the water by acting as axial flow compressors (see Figure 7.22). The axial flow

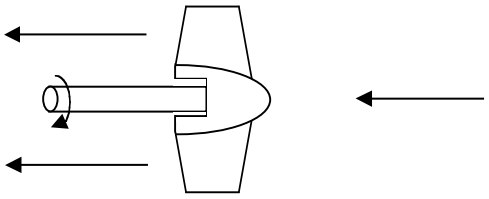

FIGURE 7.22 Axial flow pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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TABLE 7.4
Operating Characteristics for Centrifugal Pumps[16]

Characteristics	Radial-Flow	Mixed-Flow	Axial-Flow
Flow	Even	Even	Even
Effect of head on:			
A. Capacity	Decrease	Decrease	Decrease
B. Power required	Decrease	Small decrease to large increase	Large increase
Effect of decreasing head on:			
A. Capacity	Increase	Increase	Increase
B. Power required	Increase	Slight increase to decrease	Decrease
Effect of closing discharge valve on:			
A. Pressure	Up to 30% increase	Considerable increase	Large increase
B. Power required	50-60% decrease	10% decrease, 80% increase	80–150% increase

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

pump has a single inlet impeller with flow entering and exiting along the axis of rotation (along the pump drive shaft). Specific speed is greater than 9000. The pumps are used in low-head, large-capacity applications, such as:

1. Municipal water supplies
2. Irrigation
3. Drainage and flood control
4. Cooling water ponds
5. Backwashing
6. Low service applications (e.g., they carry water from the source to the treatment plant)

7.10.4 Characteristics and Performance Curves

Earlier we provided a general discussion of pump characteristic curves. In the following sections, we specifically discuss pump characteristics and performance curves directly related to the centrifugal pump.

The centrifugal pump operates on the principle of an energy transfer, and, therefore, has certain definite characteristics that make it unique.

Many manufacturers produce pumps of similar size and design, but they vary somewhat because of the design modifications made by each manufacturer. Operating characteristics for various types of centrifugal pumps are reported in Table 7.4.

The type and size of the impeller limit the amount of energy that can be transferred to the water, the characteristics of the material being pumped, and the total head of the system through which the liquid is moving. A series of performance graphs or curves best describes the relationship among these factors. The sections that follow describe centrifugal pump performance curves in greater detail.

Note: Garay[17] points out that performance curves for centrifugal pumps are different in kind from curves drawn for positive displacement pumps. This is the case because the centrifugal pump is a dynamic device, in that the performance of the pump responds to forces of acceleration and velocity. Note that every basic performance curve is based on a particular speed, a specific impeller diameter, impeller width, and fluid viscosity (usually thought of as the viscosity of water). While impeller diameter and speed can usually be manipulated within the design of a specific casing, the width of the impeller cannot be changed significantly without selecting a different casing.

7.10.4.1 Head-Capacity Curve

As might be expected, the capacity of a centrifugal pump is directly related to the total head of the system. If the total head on the system is increased, the volume of the discharge will be reduced proportionately. Figure 7.23

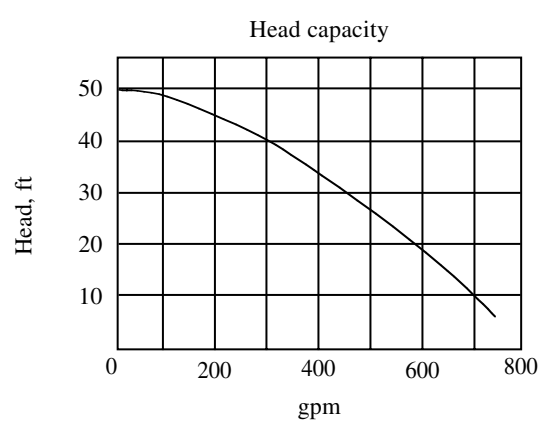

FIGURE 7.23 Head-capacity curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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illustrates a typical H-Q curve. While this curve may change with respect to total head and pump capacity based upon the size of the pump, pump speed, and impeller size and type, the basic form of the curve will remain the same. As the head of the system increases, the capacity of the pump will decrease proportionately until the discharge stops. The head at which the discharge no longer occurs is known as the cut-off head.

As discussed earlier, the total head includes a certain amount of energy to overcome the friction of the system. This friction head can be greatly affected by the size and configuration of the piping and the condition of the system's valving. If the control valves on the system are closed partially, the friction head can increase dramatically. When this happens, the total head increases and the capacity or volume discharged by the pump decreases. In many cases, this method is employed to reduce the discharge of a centrifugal pump. It should be remembered that this does increase the load on the pump and drive system, causing additional energy requirements and additional wear.

The total closure of the discharge control valve increases the friction head to the point where all the energy supplied by the pump is consumed in the friction head and is not converted to pressure head. Therefore, the pump exceeds its cut-off head and the pump discharge is reduced to zero. Again, it is important to note that although the operation of a centrifugal pump against a closed discharge may not be as hazardous as with other types of pumps, it should be avoided because of the excessive load placed on the drive unit and pump. There have also been documented cases where the pump produced pressures higher than the pump discharge piping could withstand. In these cases, the discharge piping was severely damaged by the operation of the pump against a closed or plugged discharge.

7.10.4.2 Efficiency Curve

Note: Efficiency represents the percentage of useful water horsepower developed by the horsepower required to drive the pump.

Every centrifugal pump will operate with varying degrees of efficiency over its entire capacity and head ranges. The important factor in selecting a centrifugal pump is to select a unit that will perform near its maximum efficiency in the expected application. Figure 7.24 illustrates a typical E-Q curve for a centrifugal pump. This particular curve is specific to one pump, with a specified specific speed, impeller size, type and inlet, and discharge size. If any of these factors are changed, the efficiency curve for the pump will also change.

For ease of comparison of the H-Q and E-Q curves for a particular pump, it is common practice to print both curves on a single sheet of graph paper as shown in Figure 7.25.

It is also common practice to use this same procedure to illustrate the H-Q or E-Q curves for a series of pumps

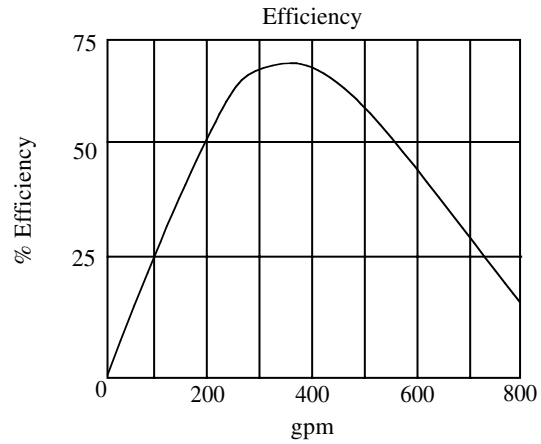

FIGURE 7.24 Efficiency curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

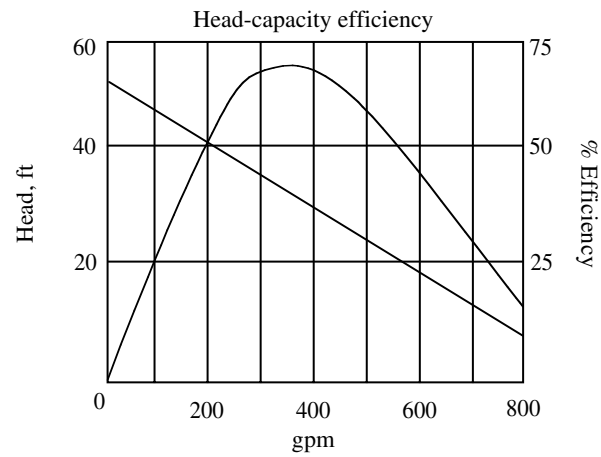

FIGURE 7.25 Head-capacity efficiency curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

that use the same volute casing size and inlet and discharge size, but may have the capability to operate at different speeds or with different sized impellers. In this instance, the head capacity of each pump configuration is shown on the graph with efficiency being shown as zones or regions. Figure 7.26 illustrates the combined curves for a single model pump that has the capability to operate with several different sized impellers and at several different speeds.

7.10.4.3 Brake Horsepower Curves

In addition to the H-Q and E-Q curves, most pump literature includes a graph showing the amount of energy in horsepower that must be supplied to the pump to obtain the performance shown in the head capacity curve. To afford easy use of this information, the brake horsepower

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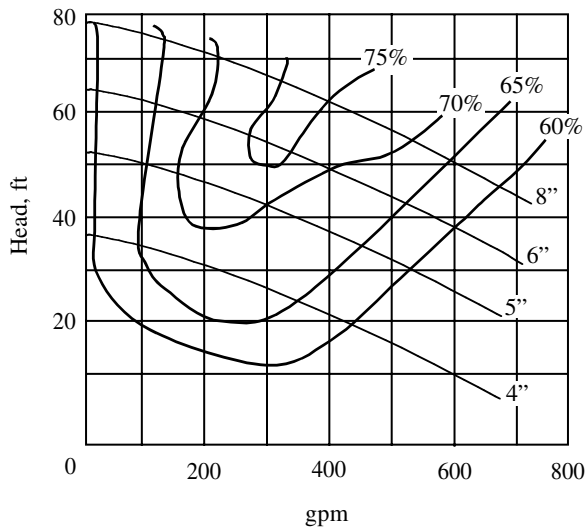

FIGURE 7.26 Head-capacity efficiency curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

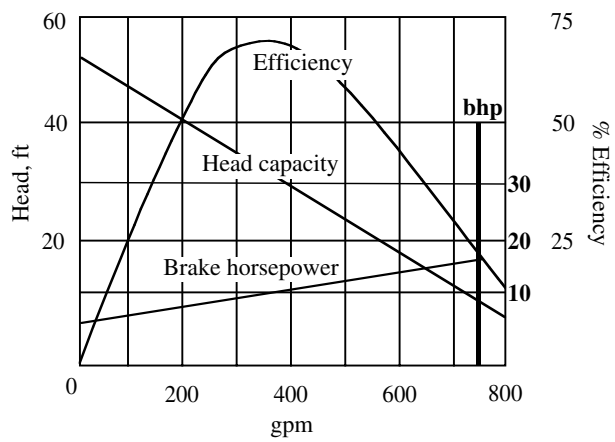

FIGURE 7.27 Head-capacity efficiency brake horsepower curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

curve is usually incorporated into the previous two curves on a single chart as shown in Figure 7.27.

As was the case for the E-Q curve, this can also be shown for all the pumps within a given series on a single combined chart (commonly abbreviated the P-Q curve). This chart will normally show the required brake horsepower as a series of lines on the chart (see Figure 7.28).

7.10.5 Advantages and Disadvantages of a Centrifugal Pump[18]

While the centrifugal pump has many advantages that make it one of the most widely used types of pumps, it also has a few disadvantages. Both the advantages and

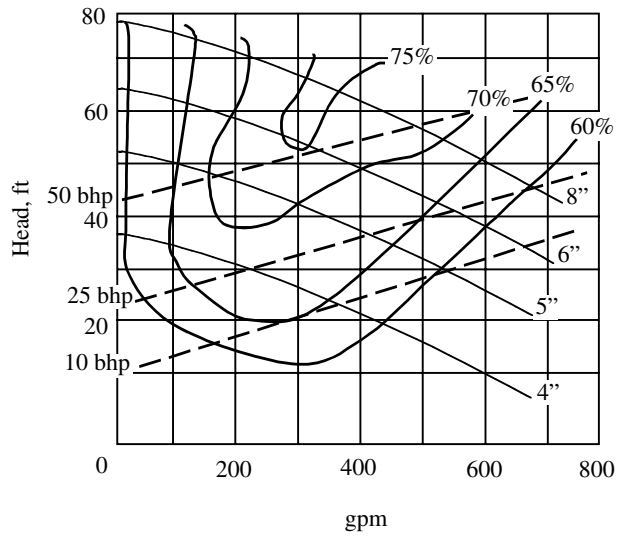

FIGURE 7.28 Head-capacity efficiency brake horsepower curve. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

disadvantages of centrifugal pumps are discussed in the following sections.

7.10.5.1 Advantages

The advantages of the centrifugal pump include the following:

1. Construction — The centrifugal pump consists of a single rotating element and a simple casing that can be constructed using a wide assortment of materials. If the material to be pumped is highly corrosive, the pump parts that contact the liquid can be constructed of lead or other material that is not likely to corrode. If the material being pumped is highly abrasive (such as grit or ash from an incinerator), the internal parts can be made of abrasion resistant material or coated with a protective material. Moreover, the simple design of a centrifugal pump allows the pump to be constructed in a wide variety of sizes and configurations. No other pump currently available has the range of capacities or available applications.
2. Operation — The operation of a centrifugal pump is both simple and relatively quiet. The average operator with a minimum amount of training can be capable of operating pumping facilities that use centrifugal-type pumps. Moreover, the pump can withstand a great deal of improper operation without major damage.
3. Maintenance — Routine preventive maintenance requirements for the centrifugal-type

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pump are not as demanding as those associated with some of the other pumping systems. While there is a requirement to perform a certain amount of preventive maintenance, the skills required to perform this maintenance are normally considered less complex than those required for other pumping systems.

4. Wide tolerance for moving parts — The design of the centrifugal pump does not require that all moving parts be constructed to very close tolerances. Therefore, the amount of wear on these moving parts is reduced and the operating life of the equipment is extended.
5. Self-limitation of pressure — Due to the nature of the pumping action, the centrifugal pump will not exceed a predetermined maximum pressure. Therefore, if the discharge valve is suddenly closed, the pump cannot generate additional pressure that might result in damage to the system or a hazardous working condition. The power supplied to the impeller will only generate a specified amount of pressure (head). If a major portion of this pressure or head is consumed in overcoming friction or is lost as heat energy, the pump will have a decreased capacity.
6. Adaptability to high speed drive systems (electric motors) — The centrifugal pump allows the use of high-speed, high-efficiency drive systems. In situations where the pump is selected to match a specific operating condition that remains relatively constant, the pump drive unit can be used without the need for expensive speed reducers.
7. Small space requirements — For the majority of pumping capacities, the amount of space required for installations of the centrifugal-type pump is much less than that of any other type of pump.
8. Rotary rather than reciprocating motion — Because of the centrifugal pump's fewer number of moving parts, space and maintenance requirements are significantly reduced.

7.10.5.2 Disadvantages

The advantages of the centrifugal pump include the following:

1. Incapable of self-priming — Although the centrifugal pump can be installed in a manner that will make the pump self-priming, it is not truly capable of drawing liquid to the pump impeller unless the pump casing and impeller are filled with water. [Note: If a suction head (positive pressure on the suction side of the pump) exists, the unit will always remain full whether on or off, but with a suction lift, water tends to run back out of the pump and down the suction line when the pump stops.) The bottom line is that if for any reason the water in the casing and impeller drains out, the pump would cease pumping until this area is refilled.

Note: The previous point is important primarily because many people hold the misconception that a centrifugal pump sucks water from its source, and that it is this sucking action that conveys the liquid along its distribution network. The fact that a centrifugal pump must be filled with water (primed) before it can perform its pumping action points out that the pump actually forces the water to move, instead of sucking the water to move it. Because of its need to be primed, it is normally necessary to start a centrifugal pump with the discharge valve closed. The valve is then gradually opened to its proper operating level. Starting the pump against a closed discharge valve is not hazardous provided the valve is not left closed for extended periods.

Note: While it is normally the procedure to leave the valve closed on the start-up of a centrifugal pump, this should never be done on a positive-displacement pump.

2. Suction side air leaks — Air leaks on the suction side of the centrifugal pump can cause reduced pumping capacity in several ways. If the leak is not serious enough to result in a total loss of prime, the pump may operate at a reduced head or capacity due to the air mixing with the water. This causes the water to be lighter than normal and reduces the efficiency of the energy transfer process.
3. High efficiency range is narrow — As we have seen in the pump characteristic curves, a centrifugal pump's efficiency is directly related to the head capacity of the pump. The highest performance efficiency is available for only a very small section of the head-capacity curve. When the pump is operated outside of this optimum range, the efficiency may be greatly reduced.
4. The pump may run backwards — The centrifugal pump does not have the built-in capability to prevent flow from moving through the pump in the opposite direction (i.e., from discharge side to suction). If the discharge valve is not closed or the system does not contain the proper

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TABLE 7.5
Centrifugal Pump Applications in Water Systems[19]

Application	Function
Low service	To lift water from the storage to treatment processes or from storage to filter-backwashing system
High service	To discharge water under pressure to distribution system
Booster	To increase pressure in the distribution system or to supply elevated storage tanks
Well	To lift water from shallow to deep wells and discharge it to the treatment plant, storage facility, or distribution system
Sampling	To pump water from sampling points to the laboratory or automatic analyzers
Sludge	To pump sludge from sedimentation facilities to further treatment or disposal

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

check valves, the flow that was pumped from the supply tank to the discharge point will immediately flow back to the supply tank when the pump shuts off. This results in increased power consumption because of the frequent start-up of the pump to transfer the same liquid from supply to discharge. (Note: It may be very difficult to determine if this is occurring since the pump looks and sounds like it is operating normally when operating in reverse.)

5. Pump speed is not easily adjusted — Centrifugal pump speed usually cannot be adjusted without the use of additional equipment (e.g., speed reducing or speed increasing gears or special drive units). Because the speed of the pump is directly related to the discharge capacity of the pump, the primary method available to adjust the output of the pump other than a valve on the discharge line is to adjust the speed of the impeller. Unlike some other types of pumps, the delivery of the centrifugal pump cannot be adjusted by changing some operating parameter of the pump.

7.10.6 Water and Wastewater Applications

As previously stated, the centrifugal pump is probably the most widely used pump available at this time because of its simplicity of design and its adjustability to a multitude of applications. Proper selection of the pump components (impeller, casing, etc.) and construction materials can produce a centrifugal pump capable of transporting materials ranging from coal or crushed stone slurries to air (centrifugal blowers used for aeration). To attempt to list all of the various applications for the centrifugal pump in water and wastewater treatment would exceed the limitations of this handbook. Therefore, the discussion of pump applications is limited to those that occur most frequently in water and wastewater treatment applications.

Water applications of the centrifugal pump are listed in Table 7.5. Wastewater applications of the centrifugal pump are listed in Table 7.6.

7.11 CENTRIFUGAL PUMP COMPONENTS

> All centrifugal pumps utilize but one pumping principle: the impeller rotates the water at high velocity, building up a velocity head.[20]

In the preceding statement, Garay succinctly points out the very basic operating principle of a centrifugal pump. On the surface, the simplicity of this statement points to the simplicity of the centrifugal pump. However, the centrifugal pump is not only a simple hydraulic machine, but it is also a composite of several major components, that should be familiar to those water and wastewater maintenance operators who must perform routine maintenance on the pump. Earlier we briefly touched upon the components making up the simple centrifugal pump. In this section, we describe each of the centrifugal pump's major components (i.e., the casing, impeller, shafts and couplings, stuffing boxes, and bearings) in greater detail, including their construction and their function.

7.11.1 Casing

The basic component of any pump is the housing or *casing*, which directs the flow of water into and out of the pump. The housing surrounding the impeller of a centrifugal pump is called the *volute case*. The word volute is used to describe the spiral-shaped cross-section of the case as it wraps around the impeller; the pump casing gets larger as it nears the discharge point (see Figure 7.29a).

Important Point: If the pump casing was the same size all the way around, the water flow would be restricted and the pump could not develop its rated capacity.

In addition to enclosing the impeller, the volute case is cast and machined to provide the seat for the impeller wear rings. The volute case also includes suction and discharge piping connections. In the volute pump shown in Figure 7.29a, the pressure against the impeller is unbalanced, resulting in an unbalanced load that is taken by the bearings supporting the impeller shaft. The pump is

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TABLE 7.6
Centrifugal Pump Applications in Wastewater Systems

Application	Function
High volume pumping	Generally low speed, moderate head, vertically shafted, centrifugal pumps are used for high volume capacity
Nonclog pumping	Specifically designed centrifugal pumps using closed impellers with, at most, two to three vanes; usually designed to pass solids up to 3 in. in diameter
Dry pit pump	Depending on the exact application may be either a large volume or nonclog pump; located in a dry pit that shares a common wall with the wet well; this pump is normally placed in such a position as to ensure that the water level in the wet well is sufficient to maintain the pump's prime
Wet pit or submersible pump	Usually a nonclog-type pump that can be submerged, together with its motor, directly in the wet well; in a few instances, the pump may be submerged in the wet well while the motor remains above the water level; in these cases, the pump is connected to the motor by an extended shaft.
Underground pump stations	Using the wet well-dry well design, the pumps are located in an underground facility; wastes are collected in a separate wet well, then pumped upward and discharged into another collector line or manhole; this system normally uses a nonclog type pump and is designed to add sufficient head to the waste flow to allow gravity flow to the plant or the next pump station
Recycle or recirculation pumps	Since the liquids being transferred by the recycle or recirculation pump normally do not contain any large solids, the use of the nonclog-type centrifugal pump is not always required; a standard centrifugal pump may be used to recycle trickling filter effluent, return activated sludge or digester supernatant
Service Water Pumps	The plant effluent may be used for many purposes; it can be used to clean tanks, water lawns, provide the water to operate the chlorination system, and backwash filters; since the plant effluent used for these purposes is normally clean, the centrifugal pumps used closely parallel those units used for potable water; in many cases, the double suction, closed impeller, or turbine pump will be used.

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

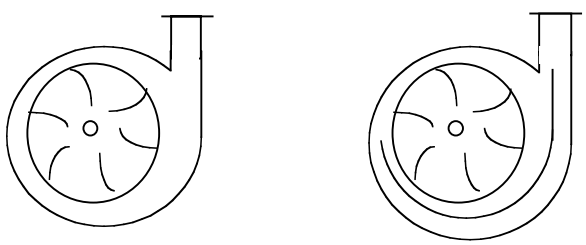

FIGURE 7.29 Types of volutes. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

designed for a radial load on the bearings, and as long as the pump performs at conditions not too far from the design point, the radial loading is accommodated. If the pump is operated at less than 30% or more than 120% of design capacity, the radial load increases drastically, causing early failure of the bearings. More significantly, the unbalanced load can cause excessive shaft deflection in areas of fine running clearances and eccentric loading of mechanical seals, resulting in leakage.[21]

To reduce this unbalanced load problem, double volute diffuser casings, such as the one shown in Figure 7.29b are used. In double volute casings, while the pressures are not uniform at partial capacity operation, the resultant forces for each 180°-volute section oppose and balance each other. The double volute incorporates a flow splitter into the casing that directs the water into two separate paths through the casing. The contour flow of the splitter follows the contour of the casing wall 180° opposite. Both are approximately equidistant from the center of the impeller; therefore, the radial thrust loads acting on the impeller are balanced and greatly reduced.

The volute casing can be classified as either solid or split casing.

7.11.1.1 Solid Casing

The solid volute casing is designed as a single piece of casting with a top or bottom opening to install or work on the impeller and wear rings. In this design, the bottom section of the volute is bolted to the intake or suction line, and the top opening of the volute is covered with the shaft assembly. End suction pumps are easy to recognize since the suction and discharge nozzles are usually at 90° angles to each other. To help simplify internal inspections of these pumps, without disassembly, the volute case is often equipped with removable inspection plates.

Note: A modification of the solid volute centrifugal pump is the back pullout pump. In this type, the volute is connected to the suction and discharge piping. The pump is pulled out from the back of the volute. This modification enables the operator to inspect or work on the pump

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without having to disconnect any piping or dismantle the pump.

7.11.1.2 Split Casings

The split case pump uses two or more sections fastened together to form the volute case. Depending on the direction of the split, these pumps can be classified as axially or radially split. Axially split casings are split parallel to the pump shaft. When half the casing is removed, the length of the shaft and the edge of the impeller are visible. Radially split casings split perpendicular to the pump shaft. When these pumps are opened, a cross-section of the shaft and the face or back of the impeller is visible. The suction and discharge for split case pumps are in the same half, parallel to each other but on opposite sides. (This arrangement allows half of the casing to be removed for easy inspection of the interior without disturbing the piping, bearings, and shaft assembly.)

The casings on volute type centrifugal pumps can be modified further to increase the volume of water handled and the pressure obtained. Most of the pumps we discuss in this handbook have a single impeller and a single suction. Volute pumps may also be multistage pumps (i.e., having two or more impellers and a corresponding number of volute cases). The discharge of the first volute serves as the suction of the second and so on. Multistage pumps with two stages are capable of obtaining twice the pressure of a comparable single stage pump. However, the volume or quantity of flow remains unchanged. To change the quantity of flow, the volute suction size is increased. Instead of a single suction, some pumps are designed with double suctions. A double suction, single-stage pump can discharge twice the volume of water discharged by a single-suction, single-stage pump with both discharging at equal pressures. To increase both the volume and pressure, a double suction, multi-stage pump could be used.

7.11.2 Impeller

The heart (and thus the most critical part) of a centrifugal pump is the impeller. The impeller's size, shape, and speed determine the pump's capacity. Although there are several designs for impellers, each transfers the mechanical energy of the motor to velocity head by centrifugal force. The central area of the impeller is called the hub. The hub is machined so the impeller can be attached securely to the pump shaft. Surrounding the hub is a series of rigid arms, called vanes, which extend outward in a curved shape (see Figure 7.30). The vanes throw the water into the volute case causing an increase in the velocity of the water. Depending on the type of impeller, the impeller vanes will vary in thickness, height, length, angle, and curvature. To increase the impeller efficiency and strengthen its construction, some impellers are enclosed by sidewalls called shrouds.

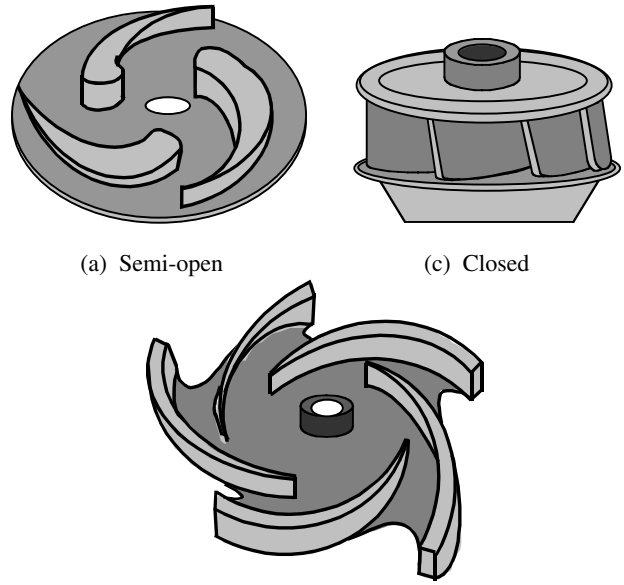

FIGURE 7.30 Centrifugal pump impellers. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Impellers can be classified as semi-open, open, or closed.

7.11.2.1 Semi-Open Impeller

Semi-open impellers (see Figure 7.30a) have only one shroud on the back of the impeller that covers the hub and extends to the edge of the vanes. When seen from the back, the shroud forms a complete circle. This feature allows the vanes to be thicker and less likely to be damaged by collision with solids or debris. The face of this impeller is left open. The shroud, besides adding structural stability, increases the efficiency of the impeller.

Semi-open impellers are most often used for pumping liquids with medium-sized solids, but they are capable of handling high solids concentrations. They are also capable of pumping high volumes of liquid at low pressures. The solids size that an open or semi-open impeller can pump depends on the closeness of the impeller to the suction side of the volute case. The distance can vary from 0.015 in. to several inches.

7.11.2.2 Open Impeller

Open impellers are designed with vanes (curved blades) that extend from the hub with no top or bottom shroud (see Figure 7.30b). Some open impellers do, however, have a partial bottom shroud to strengthen the impeller vanes. Open impellers are used to pump water with large-sized solids and water with high solids concentrations. They are generally capable of pumping high volumes of

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water at low pressures. Open impellers are more easily damaged than the semi-open or closed impeller because of the exposed vanes.

7.11.2.3 Closed Impeller

The closed impeller has a shroud on both the front and back (see Figure 7.30c). This arrangement leaves only the suction eye and the outer edge of the impeller open. With both shrouds, the impeller is quite strong and is able to maintain good pumping efficiency. The closed impeller is generally used for pumping clean water or clear wastewater. The size of the solids handled by a closed impeller pump will vary as the width of the vanes increases or decreases from one impeller to another. In contrast to open and semi-open impellers, closed impeller pumps can handle varying volumes of water and can develop very high pressures.

Nonclogging closed impellers were developed for use in wastewater pumping and to maintain the high level of pumping efficiency (while pumping varying volumes of raw wastewater at high pressures). These nonclogging impellers have large internal openings, and the distance between the shrouds is expanded so large solids will pass through them. Normally, a wastewater pump will be designed to allow passage of solids up to 3 in. in size.

Note: Impellers may also be classified according to whether they are single- or double-suction. Single-suction impellers have their flow coming into the impeller from one side only. Double-suction impellers have flow entering from both sides; therefore, they have two suction eyes instead of one. A double suction impeller does not increase the pressure obtained by the pump, yet it does double the amount of water being pumped.

7.11.3 Wear Rings

As the impeller of a centrifugal pump spins, it creates a low-pressure zone on the suction side of the impeller by the impeller eye. As the water is thrown off the impeller vanes, by centrifugal force, it creates a high-pressure zone inside the volute case. If the impeller and volute case were not matched so that the clearance between them was small, water from the high-pressure zone in the volute would flow to the low-pressure zone in the eye of the impeller, and be repumped. To prevent this from occurring (i.e., to provide physical separation between the high- and low-pressure sides), a flow restriction must exist between the impeller discharge and suction areas. Wear rings accomplish this restriction of flow (referred to as recirculation). The wear rings prevent permanent damage to the volute case and impeller. The most widely used materials for wear rings are bronze or brass alloys and are replaceable items. Bronze exhibits good resistance to corrosion and abrasion, with excellent casting and machining properties. Wear rings may be installed in the front and the back of the volute and on the impeller (see Figure 7.31).

When a wear ring is mounted in the case of a pump, it is called a casing ring. When it is mounted in the suction area of the pump, it is called a suction ring. If the suction-head ring is the only wear ring installed, both the ring and impeller must be replaced at the same time to maintain the proper clearance. If the pump has wear rings mounted on the impeller (impeller rings) and casing (suction head rings), only the wear rings will need to be replaced. The impeller can be reused provided there is no other damage. Pumps with casing or suction head rings and impeller rings have double ring construction. They have both a stationary and a rotating ring.

Wear rings can also be installed at the stuffing box, in which case they are called stuffing-box cover rings. Regardless of where the rings are installed, they are usually secured with set or machine screws along with some kind of locking device. This stops them from turning and wearing against their volute case seat. An exception to this is the impeller wear rings that sometimes are installed as pressure fit or shrink fit pieces (instead of screws) to secure them.

The clearance between the wear rings should be checked whenever a pump is opened for routine inspection or maintenance. Check the manufacturer's technical manual for proper clearance data.

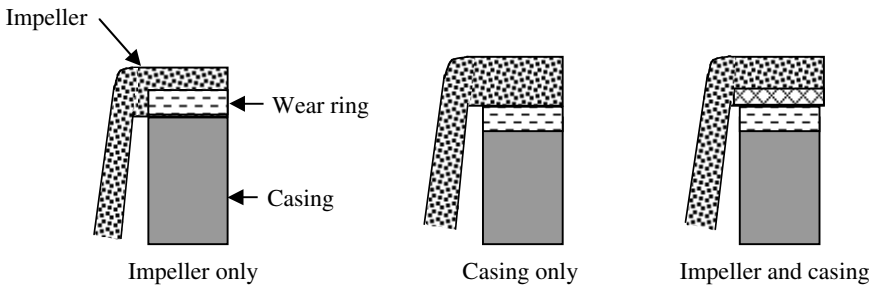

FIGURE 7.31 Wear ring arrangements. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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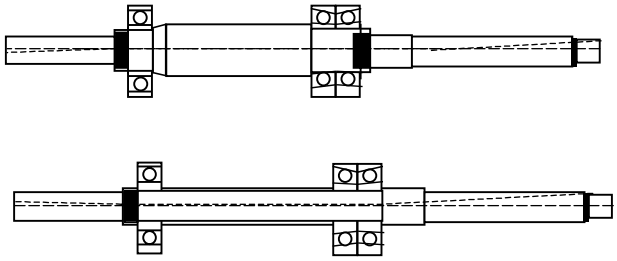

FIGURE 7.32 Pump shafts for centrifugal pumps. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Note: If a pump does not have wearing rings, worn parts must be replaced or rebuilt. On some small pumps, parts replacement may be inexpensive. On large pumps, the cost of wearing rings is far less than the cost of replacing the worn parts.

7.11.4 Shafts, Sleeves, and Couplings

Important to the operation of any centrifugal pump and drive unit is the shafting, sleeves, and couplings used to connect the drive unit to the pump.

7.11.4.1 Shafting

Shafting for a centrifugal pump consists of a main pump shaft plus possible intermediate shafts for connecting drive units where the pump and drive are separated from each other. The main pump shaft (see Figure 7.32) is a solid shaft constructed of high quality carbon or stainless steel to increase its resistance to wear and corrosion. (Note: Although corrosion-resistant materials are expensive, it is usually good practice to install a high-quality shaft despite the higher initial cost.) The shaft supports the rotating parts of the pump and transmits mechanical energy from the drive unit to the pump impeller. A common method used to secure the impeller to the shaft on double-suction pumps involves using a key and a very tight fit. Because of the tight fit, an arbor press or gear puller is required to remove an impeller from the shaft.[22] In end-suction pumps, the impeller is mounted on the end of the shaft and held in place by a key nut.

The shaft is designed to withstand the various forces acting on it and still maintain the very close clearances needed between the rotating and stationary parts. Although the shaft is of solid construction, care must be exercised when working on or around it. Slight dents, chips, or strains are capable of causing misalignment or bending of the shaft.

Closed-coupled pumps (see Figure 7.33) that have the casing mounted directly onto the drive motor have different shaft designs and construction features from frame-mounted pumps. In this pump, the impeller and the drive unit share a common shaft. The shaft that supports the impeller is actually the motor shaft that has been extended into the pump casing (see Figure 7.33).

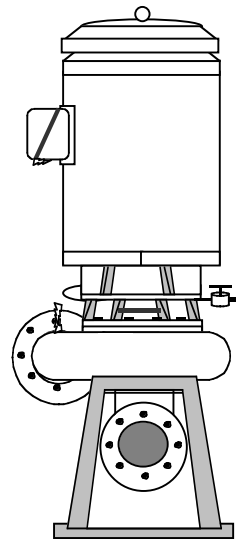

FIGURE 7.33 Close-coupled pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.11.4.1.1 Intermediate Shafts

Not all pump drive systems are designed so that the unit and the pump can be coupled directly. In many cases, distances from several inches to 100 ft separate the drive and pump units. In these situations, intermediate shafts are used to transfer energy. What is required may vary from spacers to floating or rigid shafts to flexible drive shafts.

One way to bridge the shaft separation is to use a one-piece flanged tubular spacer. A flanged tubular spacer is used for gaps up to several feet. Beyond that, the cost of manufacturing the spacer is prohibitive. The spacer is connected to the flanges of the coupling and bridges the gap between the shafts.

Floating shafts accomplish the same task as a spacer, but they are constructed differently. Floating shafts are made by attaching a flange to a piece of solid or tubular shafting by a mechanical key or by welding. This construction is less expensive than the one-piece spacer is. However, like the spacer, the flanges on the ends of the shaft connect directly to the coupling flanges. Long sections of floating shaft need to be supported by line bearings at intermediate supports or floors. Floating shaft arrangements are widely used on horizontal pump applications and are especially common on vertical systems. Axial thrust loads in a floating shaft system is compensated for by the pump's thrust bearing. Therefore, the couplings between the shaft segments can be of the flexible type.

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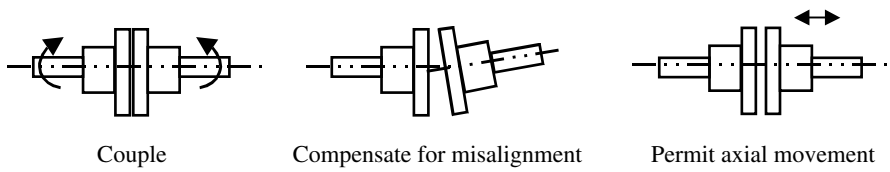

FIGURE 7.34 Coupling requirements. (Adapted from Renner, D., *Hands-On Water/Wastewater Equipment Maintenance,* Technomic Publ., Lancaster, PA, 1999, p. 122.)

Some pumps are designed with only a single line bearing associated with the pump. In these situations, the axial thrust load is taken up by the thrust bearing in the drive unit. In a pump system of this kind, rigid intermediate shafts and couplings are required. The pump and drive unit couplings and those on intermediate shafts must be rigid if the axial thrust is to be transmitted to the drive unit. Bearings associated with this system must only provide lateral support; in other words, they are line bearings.

In many vertical and horizontal pump applications, flexible drive shafts are used as intermediate shafts. In these applications, universal joints with tubular shafting can be substituted for flexible couplings when one of the following occur:

1. There is a need for critical alignment.
2. The space to be spanned is considerable.
3. There is a possible need to permit large amounts of motion between pump and drive unit.

Flanges are used to fit the pump and drive unit shafts to the universal joints. These joints are splined to allow movement of the intermediate shafts; therefore, pump thrust has to be taken up by combination pump thrust and line bearing. Intermediate bearings are required to steady the shafts. These bearings do not take on any radial loads since these are taken by the universal joints.

7.11.4.2 Sleeves

Most centrifugal pump shafts are fitted with brass or other nonferrous metal sleeves. Sleeves protect the shaft (from erosion and corrosion) and provide a wearing surface for packing or a place to mount the mechanical seals. (Note: Permitting the sleeves to take the wear from the packing rather than the shaft keeps maintenance costs and time to a minimum, compared with the replacement of a shaft.[23]) Shaft sleeves serving other functions are given specific names to indicate their purpose. For example, a shaft sleeve used between two multistage pump impellers in conjunction with the interstage bushing to form an interstage leakage point is called an interstage or distance sleeve.[24]

7.11.4.3 Couplings

To allow energy transfer from the drive unit or motor to the pump, these units must be connected; that is, they must be coupled. Renner points out that the primary duty of a coupling is to transmit motion and power from one source (drive unit) to another (the pump).[25] To accomplish this, couplings have to meet three basic design requirements (see Figure 7.34):

1. Couple two rotating shafts together to transmit power and motion from one machine to another.
2. Compensate for any misalignment between the two rotating members.
3. Allow for axial or end movement between the coupled shafts.

7.11.4.3.1 Coupling Categories

Pump couplings are grouped into two broad categories:

1. Rigid couplings
2. Flexible couplings

7.11.4.3.1.1 Rigid Couplings

Rigid couplings, like all couplings, are used to transfer energy. Their rigid construction, however, allows for no shaft misalignment. If misalignment does exist when a rigid coupling is used, the coupling and pump and motor bearings will wear very quickly. Two commonly used types of rigid couplings are the flange and split couplings.

Note: Coupling Misalignment — When connecting two shafts, it is possible to have three different kinds of misalignment. Angular misalignment is where the flat surfaces of the ends of the shafts are not parallel with each other (see Figure 7.35). Parallel misalignment (see Figure 7.36) is where the center of the two shafts are not directly over each other. The third type of misalignment is a combination of both angular and parallel.

Flanged couplings — A properly flanged coupling consists of two flanges; one attached to each shaft as shown in Figure 7.37. Each flange has a replaceable center bush-

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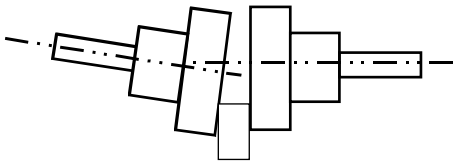

FIGURE 7.35 Angular misalignment. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

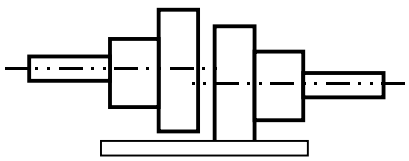

FIGURE 7.36 Parallel misalignment. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

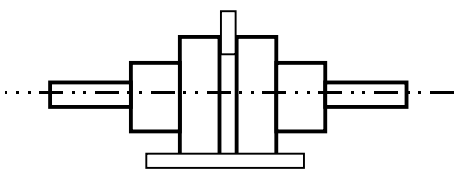

FIGURE 7.37 Two flanges correctly aligned. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

ing with a keyed slot. The keyed slot matches the shaft key and the bearing can be changed to match the different shaft diameters. When properly installed, the flanges are held together by bolts. The bolts, however, do not function in energy transfer. The frictional force of the two flange faces touching transfers energy from one shaft to another.

Split couplings — The split coupling is a tubular coupling that is split axially and held together and around the shaft by bolts. One half of the coupling is keyed and matches up with the keys of the two shafts. The split coupling offers the advantage of easy installation and removal. Its long tubular shape allows for a certain amount of impeller adjustment.

Note: Rigid couplings find their widest use on vertical mounted pumps.

7.11.4.3.1.2 Flexible Couplings

Flexible couplings allow the transfer of energy and compensate for small amounts of shaft misalignment. Flexible couplings are mechanically flexible or materially flexible. There are several types available.

Note that the type of flexible coupling used for each pump application varies with the horsepower of the drive unit, speed of rotation, shaft separation, amount of misalignment, cost, and reliability requirements. The few discussed previously are not the only ones available. If a coupling needs to be replaced at your facility, the manufacturer's literature or representative should be consulted.

Mechanically flexible couplings — Mechanically flexible couplings compensate for misalignment between two connected shafts by providing internal clearances within the design of the coupling. An example of this is the chain coupling and gear coupling:

1. Chain coupling — A chain coupling consists of a gear attached to each shaft with a double width chain wrapped around the two gears. The spacing between the faces of the gears and the flexibility in the chain compensate for misalignment. This type of coupling is limited to low speed equipment and should be surrounded by housing for safety reasons. Lubricant is often placed inside the housing to reduce friction and extend the life of the coupling.
2. Gear coupling — The gear coupling consists of a gear assembly keyed onto each shaft and surrounded by housing with corresponding internal gears. The self-adjusting gear assemblies compensate for misalignment. Like the chain coupling, the housing of the gear coupling should have a clean supply of lubricant to reduce wear and extend coupling life.

Materially flexible — Materially flexible couplings rely on flexible elements designed into the coupling to compensate for misalignment. Examples of this type of coupling include the jaw coupling, flexible disc coupling, and flexible diaphragm coupling:

1. Jaw coupling — The jaw coupling is one of the most common and least expensive of the materially flexible couplings. It consists of two flanges, one keyed on each shaft, with each flange having three triangular teeth. An elastic piece of rubber, the spider, separates the flanges and teeth and helps transfer the energy. The jaw coupling compensates for all types of misalignment, but can contribute to vibration in well-aligned units.
2. Flexible disc coupling — The flexible disc coupling consists of two flanges similar to those on the flange coupling that are keyed, one on each shaft. Each flange has pins protruding from it that pass through a flexible circular disc and into a slot in the other flange. The flexible disc compensates for any misalignment between the shafts. The flexible disc coupling can compensate up to 2° angular and 1/32 in. parallel misalignment.
3. Flexible diaphragm — The flexible diaphragm coupling consists of two flanges, one keyed on

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each shaft with a rubber or synthetic diaphragm enclosing the space around the flanges. These couplings can handle up to 4° angular and 1/8 in. parallel misalignment.

7.11.5 Stuffing Box and Seals

Sealing devices are used to prevent water leakage along the pump-driving shaft. Shaft sealing devices must control water leakage without causing wear to the pump shaft. There are two systems available to accomplish this seal: the conventional stuffing box or packing assembly and the mechanical seal assembly.

7.11.5.1 Stuffing Box or Packing Assembly

The stuffing box of a centrifugal pump is a cylindrical housing, the bottom of which may be the pump casing, a separate throat bushing attached to the stuffing box, or a bottoming ring. There are a number of different designs of stuffing boxes for pumps used in water and wastewater plants.

7.11.5.1.1 Packing Gland

At the top of the stuffing box is a packing gland (see Figure 7.38). The gland encircles the pump shaft or shaft sleeve and is cast with a flange that slips securely into the stuffing box. Stuffing box glands are manufactured as a single piece split in half and held together with bolts. The advantage of the split gland is the ability to remove it from the pump shaft without dismantling the pump.

7.11.5.1.2 Packing Material

The sealing material placed inside the stuffing box is a *packing material*. In conventional pumping systems, the stuffing box or packing assembly is generally used to seal the pump. The type of packing used varies from operation to operation depending on the type of service the pump is designed for.

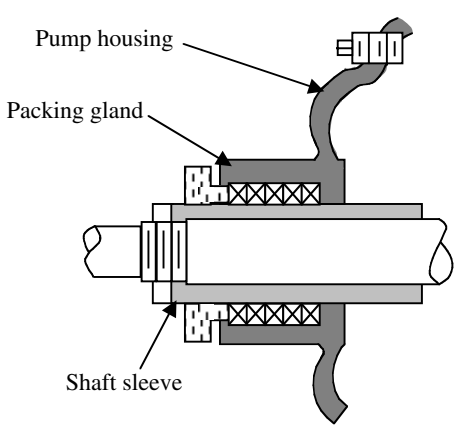

FIGURE 7.38 Solid packed stuffing box. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

The materials most commonly used for packing in pumps employed in water and wastewater operations include flax or cotton. However, there are a number of different kinds of packing, including metallic foil or synthetic substances like Teflon®, that are used or recommended for use to meet varying temperature, pressure, and liquid composition conditions. Generally, the raw materials are woven or braided to make continuous square shaped strands. Other patterns, like circular braided strands, are also available. The strands are sometimes wire reinforced and usually contain graphite or an inert oil lubricant that helps bond the braided strands together and reduce the friction between the stationary packing and the rotating shaft.

Packing is purchased in either continuous rope-like coil, with a square cross-section, or as preformed die-molded rings. When the rope-like packing is used, it is cut in sections to make up the number and size of the rings required. Some maintenance personnel prefer, where possible, to use the die-molded rings. This is because they ensure an exact fit to the shaft or shaft sleeve and the inside wall of the stuffing box — a uniform packing density throughout the stuffing box. Precut rings are generally available in exact sizes and numbers for repacking most pumps.

7.11.5.1.3 Lantern Rings

As mentioned, the purpose of the stuffing box or packing assembly is to seal the opening where the pump shaft passes into the pump. This prevents air from leaking into the pump or the pumped water from leaking out (except for a controlled amount). When either of these conditions exists, pump efficiency decreases. To seal the opening, packing is placed inside the stuffing box and the packing gland applies pressure to it. This squeezes the packing and forces it to fill the area between the shaft and the stuffing box wall. This seals the area. However, when operating, the friction and heat buildup between the stationary packing and the rotating shaft destroy the packing. The packing, although it is lubricated, quickly becomes worn and hard. This destroys the seal and possibly damages the shaft. To prevent this from occurring, a lantern ring is placed in the stuffing box along with the packing, directly across from an opening in the stuffing box.

The lantern ring or seal cage (see Figure 7.39) is a circular brass (metallic) or plastic ring; it is split into equal halves and placed around the pump shaft or shaft sleeve inside the stuffing box. The lantern ring has an I-beam construction and holes that are drilled through it.

The lantern ring allows sealing liquid to flow around and through the lantern ring to lubricate and cool the packing and aid in sealing the pump. The location of the lantern ring inside the stuffing box is determined when the pump is manufactured. It is very important when repacking a pump that the lantern ring be replaced in the

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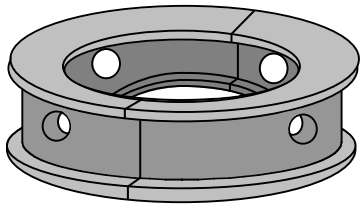

FIGURE 7.39 Lantern ring. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

proper sequence along with the packing to ensure the proper distribution of the sealing liquid.

Experience has demonstrated that it is possible to order the same type pump from a manufacturer with the lantern ring located in different positions. Having the lantern ring located closer to the inner portion of the pump diverts greater quantities of sealing liquid into the pump; this helps to keep the pumped material out of the stuffing box more effectively. This could be very important when pumping gritty wastewater or sludges. These liquids can be very abrasive on the pump shaft, sleeve, or packing.

7.11.5.1.4 Sealing Liquid

The sealing liquid piped into the stuffing can be fed from internal or external sources. When the water being pumped is clean and clear and will not damage the packing, the sealing liquid can be fed from the discharge side of the pump. Either external or internal piping does this. When the material being pumped is abrasive or would damage the packing, an external source is used as a sealing liquid. A small seal pump then pumps the external seal liquid into the stuffing box. (Note: The sealing liquid for an externally sealed pump is generally clean water, but some installations use oil seals.)

Note: If drinking water is used for seal purposes, a cross-connection prevention device must be included in the system.

In summary, the rings of packing help seal the pump; the lantern ring, placed between the packing, helps to feed the sealing liquid under pressure into the stuffing box to form an air-tight seal of the pump. The sealing liquid for an externally sealed pump is generally clean water, but some installations use oil seals.

7.11.5.2 Mechanical Seals

Mechanical seals are used in many pumps to prevent water (or other liquid) leakage. Mechanical seals might be chosen over packing on a given application for three reasons. First, mechanical seals provide a better fluid seal than packing. Second, mechanical seals usually require less maintenance than packing. Third, mechanical seals can withstand higher pressure than stuffing boxes.[26]

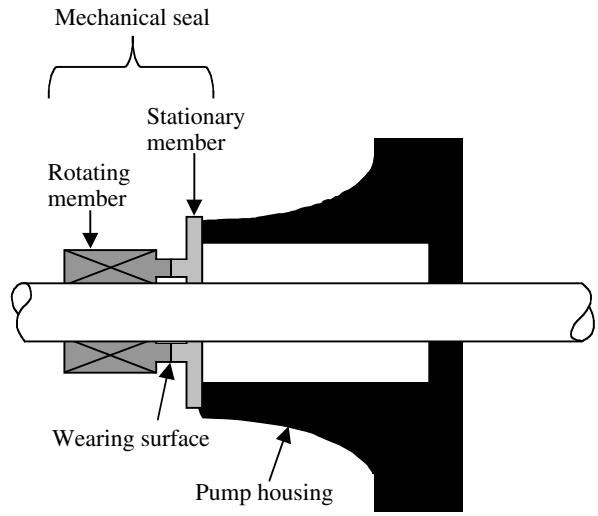

FIGURE 7.40 Typical mechanical seal. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

Note: Mechanical seals have many advantages over the stuffing box and its inherent problems of maintenance and water leakage. However, when mechanical seals fail, the entire pump must be disassembled and the units completely replaced.

Recall that when packing is used to seal a pump, the sealing surface is between the packing and the shaft or shaft sleeve. This surface is parallel with the shaft of the pump. However, if mechanical seals are used, the sealing surface is perpendicular to the pump shaft (see Figure 7.40). A mechanical seal consists of two rings with highly polished surfaces. These surfaces run against one another. One surface, the rotating element, is connected to the pump shaft and the other is connected to the stationary portion of the pump (see Figure 7.40). The stationary element of a mechanical seal is generally spring loaded to ensure continuous contact between the two polished surfaces — this fine finish is important if the seal surfaces are to match and seal properly. Very small quantities of sealing liquid is allowed to flow across the faces in order to complete the seal, as well as lubricate and cool the faces. This cuts down on the wear and increases the life of the mechanical seal.

New seals that are installed properly with the specified clearances have negligible leakage. The flow past the faces is almost nonexistent. With time and wear, a small amount of leakage has to be expected. Once the leakage reaches excessive proportions, the entire seal has to be replaced.

7.11.5.2.1 Mechanical Seals: Sealing Points

All mechanical seals have three primary sealing points. The first is the area between the stationary element and the seal housing. This area is sealed with regular gaskets or O-rings.

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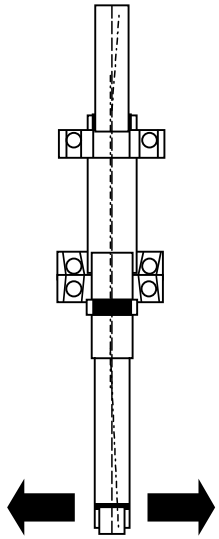

FIGURE 7.41 Radial forces. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

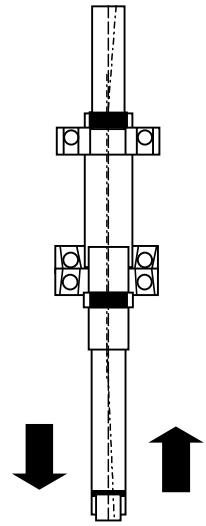

FIGURE 7.42 Thrust forces. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

The second is between the rotating element and the shaft. This is also sealed by O-rings. The third is between the polished faces. The seal water flow and the very close contact between these faces achieve this seal. To increase the life of the mechanical seal and achieve a tight seal, the surface of the polished faces are made of dissimilar materials. For example, one face might be made of stainless steel while the other one is a synthetic Teflon material.

7.11.6 Bearings

Simply, a bearing is a supporting surface that separates a stationary and a moving object. Generally, bearings are thought of as something that supports a rotating shaft. In a centrifugal pump, bearings maintain the alignment between the rotating parts (shaft and impeller) and the stationary parts (the case and frame). To maintain proper alignment, bearings must be able to work under varying loads. This load or force varies with the type of pump and the location of the bearing in the system. As the load or force varies, the bearings used to compensate also vary.

To maintain proper alignment, bearings work against radial and thrust loads. Radial forces push or pull the shaft and impeller out of alignment in directions perpendicular to the shaft (see Figure 7.41). Thrust forces push or pull the components out of alignment parallel to the shaft (see Figure 7.42). Bearings must maintain both the radial and axial positioning of the shaft and impeller.

Their function, position, and type of construction can describe bearings used for centrifugal pumps. Bearings that maintain the radial positioning of the shaft or impeller are called line bearings. Those that maintain axial positioning are thrust bearings. In many cases, thrust bearings can play a dual role, providing both radial and axial positioning.

In relation to the pump and motor or drive assembly, the terms inboard and outboard are used to describe the position of the bearings. In overhung impeller pumps, the inboard bearing is the one nearest the impeller. The outboard bearing is the one that is farther away. Horizontal pumps have bearings at each end of the pump; the inboard bearing is located between the casing and the coupling, while the outboard bearing is located on the other side of the casing. In horizontal pumps, thrust bearings are usually placed at the outboard end, while line bearings are used on the inboard side. All centrifugal pumps have a thrust bearing, which is usually outboard; this bearing may also act as a radial bearing and may be a single-row antifriction bearing exactly like the outboard.[27]

Nearly all types of bearings have been used on centrifugal pumps. The physical construction of the bearing helps to identify the type of bearing and its function. Bearings in general fall into two major categories: sliding contact bearings and rolling contact bearings. In the past, sliding contact bearings, also called plain or sleeve bearings, were once the bearing of choice; they now have been almost entirely replaced by rolling contact bearings for use on pumps. Antifriction rolling contact-type bearings are most often used in centrifugal pumps. This type includes ball bearings and roller bearings.

Just as bearing applications vary, so do the types used. In centrifugal water and wastewater pumps, five types of bearings find widespread use:

1. Self-aligning double-row ball bearings,
2. Single- or double-row antifriction ball bearings
3. Angular-contact ball bearings
4. Self-aligning spherical roller bearings
5. Single-row tapered roller bearings

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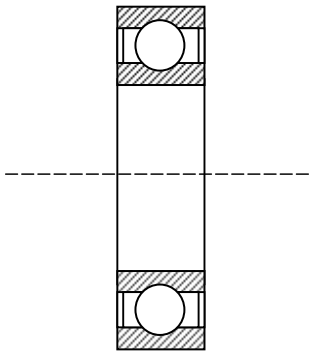

FIGURE 7.43 Single-row anti-friction ball bearing. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.11.6.1 Self-Aligning Double-Row Ball Bearing

The self-aligning double row bearing operates well against radial loads, but is only capable of withstanding very low thrust loads. For this reason, the self-aligning double row ball bearing is ideally suited for line bearing applications. It operates well under heavy loads, high speeds, and long bearing spans as long as there is no end thrust loads.

7.11.6.2 Single- or Double-Row Antifriction Ball Bearing

The single-row (deep-groove) bearing is the most commonly used bearing on all but the larger centrifugal pumps. It can withstand radial loads and reasonable amounts of thrust loading and also operates well at high speeds. It does require careful alignment between the shaft and the bearing housing. A single-row antifriction ball bearing is shown in Figure 7.43.

The double-row version of this same bearing (see Figure 7.44) has greater capacity to handle both radial and thrust loads. It is used when a single row is not sufficient to withstand the combined loads.

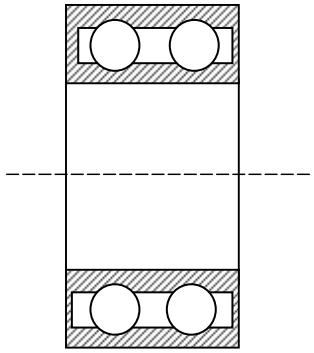

FIGURE 7.44 Double-row anti-friction ball bearing. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

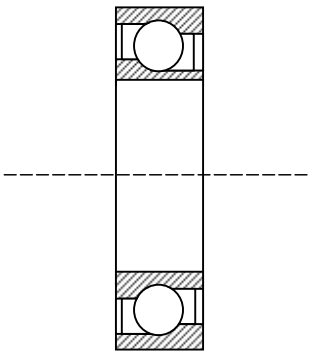

FIGURE 7.45 Single-row angular contact bearing. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

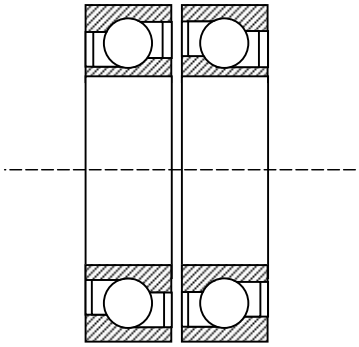

FIGURE 7.46 Back-to-back angular contact bearing. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.11.6.3 Angular Contact Bearings

The design of 40° angular contact ball bearings operates well under heavy thrust loads. The single row type (see Figure 7.45) is good for thrust loads in one direction. In most centrifugal pumps, the thrust reverses during start-up, so the thrust bearing must absorb thrust from both directions. Double angular contact bearings (as shown in Figure 7.46) within the same outer race can withstand moderate radial loads.

7.11.6.4 Self-Aligning Spherical Roller Bearings

The self-aligning spherical roller bearing can withstand both heavy radial and thrust loads. The thrust loading can also be in either direction. These bearings find their greatest use on larger shaft sizes for which the selection of suitable ball bearings is limited.

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TABLE 7.7
Common Antifriction Bearings

Type	Characteristics
Single-row deep-groove ball bearing	Good radial load and reasonable amount of thrust in either direction; requires good alignment; high speed
Angular-contact ball bearing	Heavy thrust one direction; moderate radial load; with sides flush ground, can be used in multiple numbers
Spherical roller bearing	High load capacity (both radial and thrust); thrust either direction; self-aligning.
Single-row tapered roller bearing	Good for heavy one-way thrust or combined load; predominately thrust load; requires adjustment of internal clearance.

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

7.11.6.5 Single-Row Tapered Roller Bearings

The single-row tapered roller bearing is good for heavy thrust loads in one direction and, in some cases, it can handle combined loads. This bearing does require adjustment of internal clearances.

Note: The preceding discussion of bearings is by no means complete, it is intended to provide the reader with some idea of the many different kinds of bearings that are available to meet the many different load conditions. While rolling contact bearings are widely used, they are not the only types of bearing used in pumps. Sliding contact bearings, such as sleeve or babbited bearings, have been used in many pumps.

Table 7.7 provides a summary list of common antifriction bearings and their characteristics.

7.11.6.6 Bearing Installation, Maintenance and Lubrication

When replacing bearings, the manufacturer's specifications should be followed. If not available, the manufacturer's representative should be consulted.

We pointed out earlier that bearings function to provide alignment between the moving and nonmoving parts. In doing so, there is always a certain amount of friction developed between the bearing and its guides or races. This metal to metal contact creates heat that must be transported away from the bearings in order to provide a long running life. To cool the bearing and reduce the amount of friction, oil, grease, or synthetic lubricant is applied. This lubricant must be applied to the moving parts in a thin film. Too much lubrication can increase friction and lead to excessive heat.

When a bearing is installed in a pump or along a shaft, it is placed within a housing that holds the outside of the bearing stationary, while also providing an area for applying lubrication to the bearing. This housing or seal provides a reservoir for lubrication and encloses the bearing, keeping dirt out. There are many different designs for bearing housings and they vary with the lubrication used.

7.12 CENTRIFUGAL PUMP: OPERATIONAL PROCEDURES

The proper operation of a centrifugal pump helps to ensure that the pump maintains its peak performance with minimal amounts of downtime and unexpected and costly maintenance. It is important to note that neither good operational procedures nor maintenance programs can ensure the smooth operation of any pump that has not been properly selected for its specific application. For example, if a standard centrifugal pump with cast iron casing is used to pump gritty abrasive materials, it is unlikely that the pump casing will have a long operating life no matter how conscientiously the unit is operated and maintained.

In this section, we cover important aspects related to typical operational procedures used in the proper operation of centrifugal pumps including: pump installation procedures, pump start-up procedures, normal operation, pump shutdown procedures, pump priming procedures, and procedures typically used for back flushing.

Note of Caution: The normal operation of a centrifugal pump is not complex. In fact, ease of operation remains one of the major advantages of the centrifugal pump. The level of technical skills required to operate a centrifugal pump is much less than that required for the majority of the other classifications of pumps. Nevertheless, the procedures discussed in the following are generic; they are typical of centrifugal pump operations used in many water and wastewater operations. Because the operational procedures discussed are generic and/or typical does not mean that they are the exact procedures that should be used at any particular plant for any particular centrifugal pump. You must ensure that for any specific centrifugal pump operation that the manufacturer's technical manual is the

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first source of correct operational instructions. If the manufacturer's technical manual is not available, check with the vendor and the responsible person in charge of the pump to ensure that the pump is operated in accordance with proper operating requirements.

7.12.1 Installation

Technically, pump installation may not fall within the parameters of general operation, but it can have significant impact on the routine operation of the pump.

All major reputable pump manufacturers and vendors supply specific installation instructions with their pumps. These include:

1. Pump specifications
2. Electrical service requirements
3. Foundation specifications
4. Control system specifications

These pump installation instructions (supplied by the manufacturer or vendor) should be included in the plant's equipment records.

If a centrifugal pump is to be purchased and installed by plant personnel, we recommend that the pump purchase requisition include a request for vendor installation procedures. Moreover, according to Wahren,[28] even if the delivered pump package includes installation instructions, the purchaser should consider the following items:

1. Upon receipt of the pump package, the purchaser should inspect the package for any signs of damage during transport. If damage is noted, the pump package should be immediately returned to the manufacturer or vendor. Remember, once you sign for an item (any item), you take ownership, and could end up accepting damaged goods — and become stuck with them. The purchaser should also ensure that the package conforms to the bill of lading.
2. All lifting must be per vendor's instructions. Do not use slings around nozzles or other openings not designed for lifting.
3. Remove dirt, grease, and oil from equipment feet or bottom of skid or baseplate. Ensure that the vendor provided protection from damage and corrosion for these parts during transportation and storage. Again, do not sign for any pump package where damage is apparent.
4. When positioning the pump package for mounting, the use of type 316 stainless steel, 1/4-in. thick leveling shims are preferred.
5. Generally, pump bases with four anchor bolts require a set of shims for each bolt.
6. Pump bases with six or more anchor bolts require U-type shims when positioning the pump package.
7. Wedges should not be used.
8. As a general rule, the installation tolerances are:
   A. 1/8 in. in any direction of horizontal displacement
   B. ±1/8 in. elevation
   C. 1/2° for face alignment in vertical and horizontal plane
9. The pump package should not be leveled or aligned by tightening bolts.
10. The largest flange, usually the suction flange, is the position selected for aligning the equipment.
11. If the pump and driver lie on the same baseplate or skid, disconnect the two before leveling the equipment.
12. Disconnect the coupling between the pump and the driver before positioning and leveling the equipment.
13. Make up the coupling after positioning and leveling the equipment, using the vendor's tolerances as a guide. Do not dowel the bases until hot aligning the package, if required.
14. Proceed with grouting of the equipment.
15. Use a dial indicator and reverse indication for parallel and angular coupling alignment. The tolerances must be within ±0.005 in. for both rigid and flexible couplings.
16. Misalignment causes between 50 and 70% of all pump-bearing failures, so the purchaser may want to use stricter alignment tolerance and a laser indicator to get more accurate readings.

7.12.2 Start-Up

As the case with pump installation, major pump manufacturers supply valuable information on the proper procedures to use when starting a pump for the first time or for situations where the pump is being placed back in service after removal for repair.

Again, it is essential the pump be thoroughly inspected and placed in service by someone who is familiar with the correct start-up procedure. If the pump is not put into service properly, it may be damaged or its operating life may be dramatically shortened. It should be noted that if the pump is improperly installed or started, the damage that occurs might not be covered by the pump warranty.

It is always good practice to ensure that any contract for a new pump or new pump installation also include provisions for factory trained service personnel to install, start-up, and train plant personnel on proper start-up or operational procedures. Unless the plant staff is highly experienced in the area of pump operation and mainte-

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nance, this may prove to be the least costly method to ensure proper installation and initial operation.

All technical literature supplied by the manufacturer regarding pump start-up should be maintained as part of the plant's permanent records. Moreover, in many circumstances it is highly beneficial to post written start-up procedures at the pump operation station.

For situations where the manufacturer does not provide specific instructions, the following generic procedure may be helpful in starting the centrifugal pump. (Note: Remember, the manufacturer's start-up procedures always take precedence over any other procedure.)

7.12.2.1 Start-Up Procedure

1. Inspect pump bearings and lubricate if needed. (Note: Be careful not to over lubricate the bearings — too much lubrication can be just as damaging as too little lubrication.)
2. If possible, turn pump shaft by hand to ensure free rotation.
3. Check shaft alignment and adjust if necessary.
4. Check coupling alignment and adjust if necessary.
5. Check electrical service to the pump to ensure it is wired correctly and has the appropriate service (i.e., 120, 240, 440 V …, single or three phase, etc.).
6. Check motor heaters and reset if necessary.
7. Turn motor on and then off — check rotation of the pump shaft. (Proper rotation is normally indicated on the pump case.)
8. Inspect pump control system. Does it activate the motor starter when the liquid level reaches the desired level? Does it deactivate the pump motor when the level reaches the desired cut off point? Adjust as necessary.
9. Adjust packing by tightening packing gland until nuts are finger tight.
10. Start seal water flow and allow a high rate of leakage during start-up.
11. Prime pump by filling casing and suction line.
12. Start pump in the manual mode of operation.
13. Monitor pump operation, bearing temperature, delivery rate, and discharge pressure. Record for future reference.
14. Observe operation of control system.
15. Adjust seal water flow to desired flow rate.
16. If all systems are found to be operating as designed, place pump system in auto control mode and set operation clock to record actual operating time.
17. Do not operate the pump with the discharge or suction valve closed except for a very short time, because this will damage the pump.

7.12.3 Normal Operation

Normal operation requirements for a centrifugal pump are relatively simple and straightforward. It is a matter of housekeeping, observation, lubrication, and maintenance. In general, normal operation consists of the following:

1. Careful observation of the pump operation, paying particular attention to the sounds of the operation, the amount of vibration, and operating temperature of the bearings and motor
2. Observation and adjustment of seal water flow rate (approximately 20 drops/min leakage for conventional packing)
3. Observation of control system operation
4. Cleaning control sensors
5. Observation of control valves and check valves
6. Observation of the discharge volume or pressure
7. Recording pump parameters and cumulative operating time
8. Rotating pumps to ensure even wear on available pumps (usually performed at least once per week)

7.12.4 Shutdown

As with installation, start-up and normal operation, manufacturer's instruction books also normally include very specific instructions regarding the shutdown of the pump for either routine maintenance or for extended periods. Again, since the manufacturers are the authority on their pumps and have better knowledge of each pump's requirements, these recommendations should be followed whenever possible.

In the event that this information is unavailable, the following general procedure may be of assistance to ensure that the pump is not damaged by its removal from service.

1. Place alternate pump in service.
2. Observe alternate pump's operation to ensure continued availability of pumping capacity.
3. Shut pump off.
4. Close intake and discharge control valve.
5. Close seal water valve.
6. Open circuit breaker and lockout or tagout.
7. Flush the pump to remove wastes and debris from casing. Allowing waste to remain in the pump could be detrimental to the pump and to workers. The trapped wastes could produce sufficient gases to rupture the case or create flammable or explosive conditions.
8. Perform scheduled maintenance to ensure pump is ready to return to service when necessary.

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7.12.5 Priming

Hauser[29] points out that a major deficiency of centrifugal pumps is that the pump chamber must be filled completely with water upon start-up for it to function correctly. However, to combat this deficiency, in the majority of the installations, the centrifugal pump is installed to allow gravity flow from the wet well. In this way, the pump fills by gravity, ensuring that the inside of the pump casing and impeller are constantly full (i.e., fully primed). It is essential that the casing and impeller be full of water or the pump will either not deliver any liquid or, if partially filled, will discharge at a reduced rate.

7.12.5.1 Priming Procedure

As previously mentioned, it is essential that the entire pump interior be completely filled with water and that no air be trapped within the casing. In addition to the reduced capacity associated with lack of a full prime, the pump may also be extremely noisy and may vibrate excessively. If allowed to operate for any length of time in this condition, mechanical damage to the impeller, casing, or shaft may occur. The following is a general priming procedure for the centrifugal pump:

1. Open the vent valve at the top of the casing. (Note: Depending upon the pump location, the next step will vary.)

For pumps located below the liquid level in the wet well:

2. Slowly open the valve on the intake or suction side of the pump.
3. Allow the casing to fill until liquid is leaving the pump casing from the vent valve.
4. Close the vent valve.
5. Start pump.
6. Slowly open discharge valves until fully open.

For pumps located above the level of the liquid in the wet well:

1. Open the pump suction and discharge valves.
2. Slowly and carefully, open the pump's discharge check valve to allow a back flow from the discharge line into the pump casing. (Note: If the pump is part of a multiple pump setup, the discharge line will be under pressure and extreme care must be used in opening the discharge check valve.)
3. Allow the flow to continue until water is noted at the vent valve. Close vent valve.
4. Slowly close the discharge check valve. Rapid closure of this valve could permanently damage the check valve as well as cause serious damage to the associated piping.
5. Close discharge control valve.
6. When ready to start pump, start motor and slowly open discharge valve.

In a few instances, the pump casing and impeller cannot be filled by either of the means described due to the lack of a source of water that can flow into the pump. In these cases, the pump may be manually filled. The procedure in this case is to:

1. Open the vent valve.
2. Remove plug located near the top of the casing or near the top of the discharge of the pump.
3. Pour water slowly into the pump casing until liquid is noted at the vent valve.
4. Replace plug.
5. Start pump as described previously.

If manual filling of the pump casing is not feasible or if the pump cannot be expected to maintain a prime during off periods, it may prove beneficial to install some form of vacuum system that will allow the operator to withdraw air from the casing. The removal of air will create a vacuum and will draw water from the wet well or supply tank to the pump. Although more expensive than the manual filling of the casing, it is very beneficial for pumps which required repeated priming.

7.12.6 Backflushing

In many situations, debris may be trapped within the casing or impeller. When this occurs, the pump may not discharge at its rated capacity or it will operate with more noise and vibration. To correct this problem, the pump casing and impeller must be cleaned to remove the debris. There are two methods available to accomplish this:

1. Backflush the pump
2. Manually remove the debris through the inspection ports or by disassembling the pump casing.

7.12.6.1 Backflush Procedure

Note: Check pump operation and pump prime to determine if the cause of the excessive vibration and noise is debris trapped in the casing or impeller.

1. Inspect pump to determine there is no mechanical cause for vibration.
2. Open vent valve on casing to ensure the pump is fully primed.

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3. Shut off pump.
4. Close discharge valve.
5. Slowly open discharge check valves and hold it open.
6. Turn on second pump that operates on the same discharge line.
7. Slowly open the discharge control valve on the pump requiring backflushing.
8. Allow the backflushing to continue for a few minutes.
9. Slowly close the control valve on the pump being backflushed.
10. Slowly close check valve; do not allow the valve to slam since that could cause serious damage to the valve.
11. Start pump that has been backflushed. Slowly open the discharge control valve.
12. Observe operation. If discharge is still below the normal level or the pump is still noisy and vibrating, remove the pump from service for additional maintenance.

Note: In some instances, plant personnel can utilize methods that will allow the pump to be backwashed even if there is no other pump available on the line to provide the pressure. The pump may clog frequently. If this is the case, it may be possible, under proper supervision by an experienced operator, to use a tap and valve on the pump's discharge line to connect an outside pressure source or auxiliary pump. However, never use a positive displacement pump without the necessary safety equipment to prevent excessive exposure.

Cautionary Note: Never use wastewater to flush a pump. It is important that no cross-connections be created, which would allow wastewater to enter the city water supply.

7.12.7 Manual Removal Procedure

1. Follow the shutdown procedure to isolate and shut down the pump.
2. After checking to ensure the pump's electrical circuit has been opened and properly locked or tagged out, remove inspection ports or hand holes.
3. Using a flashlight or other light source, inspect the pump casing interior.
4. Using gloves or other safety equipment, remove any debris located within the casing.
5. Flush the interior of the casing with service water.
6. If possible, rotate shaft to ensure debris has been removed.
7. Replace inspection ports.
8. Prime the pump.
9. Place the pump back in service.
10. Observe operation. If still vibrating or discharging at a reduced capacity, remove from service and lockout or tagout before disassembling to determine cause.

7.13 CENTRIFUGAL PUMP: MAINTENANCE PROCEDURES

It logically follows that with time the family home; car; lawn mower; swimming pool; heating, ventilation, and air conditioning system; and other home appliances will all need routine maintenance. Like most of the possessions we own, every centrifugal pump also requires a certain amount of routine maintenance. Whether it is a daily inspection and adjustment of the packing gland or a yearly inspection and adjustment of the shaft and coupling alignment, a centrifugal pump requires some maintenance to provide reliable service throughout its normal operational life.

7.13.1 Pump and Motor Lubrication

Lubrication (i.e., using a controlled amount of grease or oil lubricant) is probably the most important and most frequently performed of all maintenance functions. This is the case because lubrication is needed to overcome friction, reduce heat buildup, and extend the life of motor and pump bearings. The need for proper lubrication techniques cannot be overemphasized. It is important to note that both over- or under-lubrication can damage the motor and pump and create excessive downtime for pumping equipment. Accordingly, the maintenance operator in charge of lubricating the motors and pumps should be familiar with the manufacturer's recommendations for lubricants and lubrication procedures. The recommendations are supplied with the pump and motor and usually vary from pump to pump.

Note: Keep in mind that the manufacturer's recommendations normally take precedence over any other guidelines specified for pump maintenance.

7.13.2 Packing and Seal Replacement

The stuffing box should be inspected each day the pump is in operation. During the inspection, the amount of leakage should be noted. If the gland is adjusted properly, a leakage rate of from 20 to 60 drops of seal water/min is normal. Inadequate or excessive amounts of leakage are signs of possible trouble.

If the leakage is below 20 drops/min or there is no leakage, the operator should:

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1. Gradually loosen the packing gland nuts.
2. Observe the leakage rate after loosening the gland.
3. If the rate increases, assume that the gland had been over-tightened. The operator should allow the stuffing box to cool and then shut the pump down. After locking or tagging the pump out, the gland and packing should be removed. With the packing out, the shaft or sleeve can be inspected for excessive wear. If the shaft or sleeve is not damaged, the pump should be repacked following manufacturer's instructions.
4. If after loosening the gland, no leakage is observed, the pump should be shut down and locked or tagged out. At this time, the seal water supply system should be investigated following the manufacturer's troubleshooting procedures. Once the seal water problem is corrected, but before the pump is put back in service, the gland and packing should be removed and all components inspected. If there is excessive scoring of the shaft or sleeve, this should be repaired before the pump is repacked and put in service.
5. If excessive leakage is occurring, the gland should be tightened following the procedure outlined for repacking the pump. If the amount of leakage cannot be controlled, the pump should be repacked.

7.13.2.1 Packing Procedure

The following presents a common packing procedure:

Note: Experienced personnel should only accomplish the repacking and adjusting of stuffing boxes. If those with little experience must do the job, they should be cautioned against placing too much pressure on the gland. They should be informed that excessive leakage is not as damaging as too little.

1. Never try to add one or two rings to the old packing. It is false economy. Remove the old packing completely, using a packing puller if available, and clean the box thoroughly. Inspect the sleeve to make sure it is in acceptable condition. Putting new packing against a rough or badly worn sleeve will not give satisfactory service.
2. Check that the new packing is a proper type for the liquid, operating pressure, and temperature. Unless the packing is die-molded and in sets, make sure that each ring is cut square on a model of correct size.
3. Insert each ring of packing separately, pushing it squarely into the box and firmly seating it by using the packing gland or two half rings of proper length. Successive rings of packing should be staggered so the joints are 120° or 180° apart.
4. When a lantern ring is involved, make sure it is installed between the proper two rings of packing so it will be located properly for the sealing liquid supply when the box is fully packed and adjusted.
5. After all the required rings of packing have been inserted, install the gland and tighten the gland nuts firmly by hand. In doing so, watch that the gland enters the stuffing box squarely and without cracking, so the outer edge of the packing is compressed uniformly.
6. After this first tightening of the gland, back off the nuts until they are merely finger tight. When ready, start the pump and keep the gland loose so there is excessive leakage initially. Periodically tighten up slightly (one-eighth of a turn) and evenly on the gland nuts so the leakage is reduced to normal after several hours. Do not attempt to reduce the leakage too much. It must be a steady stream sufficient enough to carry away the heat generated by the packing friction.

7.13.2.2 Mechanical Seal Installation Procedure

The routine maintenance for mechanical seals involves inspecting the seals daily, ensuring that the seal water is flowing and replacing the seal when it no longer prevents leakage. Those responsible for maintenance of pumps employing mechanical seals should read the seal manufacturer's instructions for the operation and maintenance of the seal carefully. Because of the wide variation in seals being used, it is difficult to describe a step by step replacement procedure.

Note: To obtain satisfactory service and long life out of a mechanical seal, a small amount of seal water (a drop or two every few minutes) is required at all times during operating periods. A seal that runs dry will fail rapidly.

In the outline that follows, we point out a few general steps that apply to most seal replacements or installations. Again, the manufacturer's technical manual (or literature) provided with the mechanical seal is the best source of instructions and should always be used when available.

1. Shut the pump down and lockout or tagout the system.
2. Close the suction and discharge valves and remove the drain plug.
3. Dismantle the pump and inspect the shaft or shaft sleeve. If a mechanical seal is being

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installed to replace conventional packing, the shaft sleeve needs to be replaced. If the mechanical seal is being replaced with another seal, the shaft or sleeve should be cleaned with emery cloth.

4. Clean the shaft and/or sleeve to remove any filings. If the shaft or sleeve is pitted or corroded, it should be replaced.
5. Check the shaft for endplay and runout. Endplay cannot exceed 0.005 in. and the runout should be less than 0.001 in. per inch of shaft diameter. If shaft endplay or runout is excessive, the shaft bearings or the shaft should be replaced.
6. Spray or brush layout bluing on the shaft around the area of the seal housing.
7. Reinstall the seal housing and mark the location of the top of the housing on the shaft; remove the housing.
8. Using manufacturer's specifications, mark the location of the rotating element on the shaft.
9. Before installing the rotating element, check the edge of the shaft for burrs which could cut the O-ring secondary seal.
10. Remove the seal from its container; care must be taken not to damage the primary sealing faces.
11. Position the rotating element on the shaft at the marked location; fasten it down temporarily.
12. Place the stationary element into the seal housing and install the housing on the pump.
13. Using the feeler gauge, adjust the rotating element to establish the proper clearance; fasten the element in place.
14. Reassemble the pump and put it back in service; check seal operation.

7.13.3 Pump and Motor Bearing Inspection

Normally, proper application, proper lubrication, and the use of antifriction bearings on centrifugal pumps and their drive units will ensure they have a long life. As part of the normal daily operating routine, pump and motor bearing maintenance is limited to a hand check of bearing temperature. (Note: Ideally, a digital readout portable thermometer should be used to check bearing temperatures. A piece of clay and standard bulb thermometer can also be used).

Note: Daily hand checks of bearing temperature are crude but often effective method of determining bearing operating conditions.

Beyond the normal daily operating routine, bearing temperatures are routinely checked using a thermometer every month. The reading obtained should be compared with the previous readings. Normal operating temperatures run around 180°F, but temperatures vary with each installation. The actual bearing running temperature is not that important. What is important is spotting temperature increases above normal operating levels before serious damage occurs in the unit.

Rising bearing temperatures are an indication of increased friction within the bearing and a sign of problems (e.g., over-lubrication, improper pump and motor alignment, and under-lubrication). When elevated temperatures are discovered, the cause of the problem should be investigated immediately.

7.13.4 Shaft and Coupling Alignment

Shaft and coupling alignment should be inspected at least every 6 months. If there are any signs of problems because of misalignment, an inspection should be performed immediately. Correct alignment of the pump and driver and any intermediate shafting and couplings is very important to trouble-free operation. Keep in mind that a flexible coupling will not compensate for all misalignment. Noisy pump operation, reduced bearing life, excessive coupling wear, and waste of power may result from faulty alignment.

The procedures that should be followed when checking and installing a coupling are not always the same. The manufacturer determines the proper alignment procedure for any given coupling. These alignment instructions should be included in the operating manuals that are furnished with any purchased machinery. If the alignment instructions are missing, there are a few basic procedures that can be used.

7.13.4.1 Alignment Procedure

1. On new installations, the pump is leveled and a preliminary alignment is made before grouting the base plate to its foundation. After the grout has set for no less than 48 h and foundation bolts are tightened, the driver is now ready for alignment.
2. Start the alignment process with a check and correction of the angular alignment. The coupling gap should be checked with a feeler gauge or a coupling alignment indicator gauge. The check should be done in both the horizontal and vertical plane. Use shim stock no smaller than the motor feet to make any necessary corrections in angular alignment.
3. After proper angular alignment has been established, any parallel misalignment needs to be corrected. Using a straight edge, align the drive and pump unit couplings so they line up with each other on all sides. Once again, use shims

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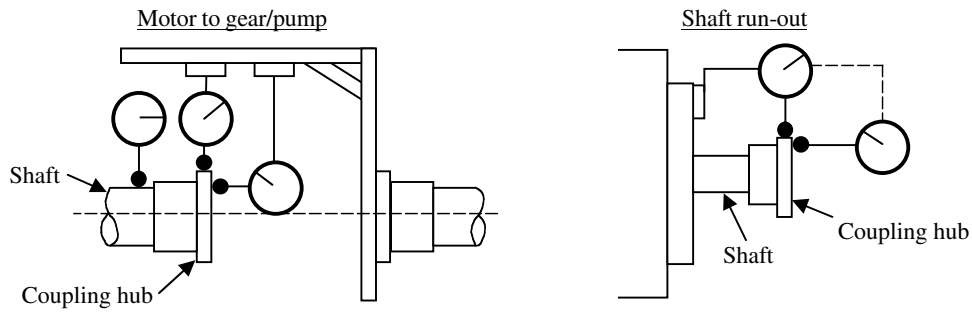

FIGURE 7.47 The use of dial indicator to align pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

to adjust the drive unit and establish proper alignment.

4. A better method of checking angular or parallel alignment is with the use of a dial indicator (see Figure 7.47).
5. Remember to recheck each alignment after making any adjustment.

7.13.4.2 Removal of Obstructions

It is often necessary to open the pump to remove obstructions that have lodged in or around the impeller or the volute. This procedure is rather basic, but certain precautions should always be taken:

1. Always shut down and lockout or tagout the system.
2. Check the suction and discharge valves to ensure they are closed.
3. Remove the vent or drain plug. This allows the pressure and water to escape from the volute.
4. After the flow has stopped, open the pump.
   A. Solid case pumps are usually equipped with removable inspection plates. After removing the plate, the internal portion of the pump is accessible.
   B. Split case pumps do not have inspection plates; however, half the casing can be easily removed for internal inspection.
5. Remove the obstruction and inspect the inside of the pump.
6. Make any necessary repairs and put the pump back together.
7. Prime the pump and put it into operation. Very slowly release any entrapped air from the volute. This is done by slowly opening the vent plug on the volute and allowing the air to escape. Caution should be taken when performing this operation because the inside of the volute is under pressure.

7.14 PREVENTIVE MAINTENANCE OF CENTRIFUGAL PUMPS

We can categorize maintenance as either reactive or preventive. Reactive maintenance occurs when equipment fails unexpectedly. Preventive maintenance occurs according to an organized method to address potential problems.

Reactive maintenance leads to a plant in a constant state of putting out fires. For maintenance, the fire is the equipment breakdown. Putting the fire out is restoring the equipment to fully operational status. The basic problem with reactive maintenance is rather obvious. To extend our analogy, preventing a fire is always better than fighting a fire.

Effective preventive maintenance prevents a lot of fires — unscheduled equipment shutdowns.

Which do you prefer?

The centrifugal pump (and several other types of pumps) used in water and wastewater operations is considered to be a relatively low maintenance hydraulic machine. However, there is a direct relationship between the service obtained from the pump and the preventive maintenance (i.e., the scheduling and performance of regular maintenance functions from inspections through overhaul or replacement; typically consists of planned or routine maintenance) that the pump receives.

In many instances, a pump may be capable of providing excellent service for an extended period with little or no attention. However, if there is no planned maintenance (i.e., the periodic scheduled removal of equipment from service for the disassembly and inspection of the internal working parts), or routine maintenance (i.e., daily general inspection and testing, including regular lubrication, performed as a part of the regular operation of the plant), the end result will be a shortened service life and eventual decay of the equipment.

The manufacturer's technical manual is always the best source of specific maintenance information. Based on service history, case study, and controlled testing, the manufacturer typically outlines those items that require

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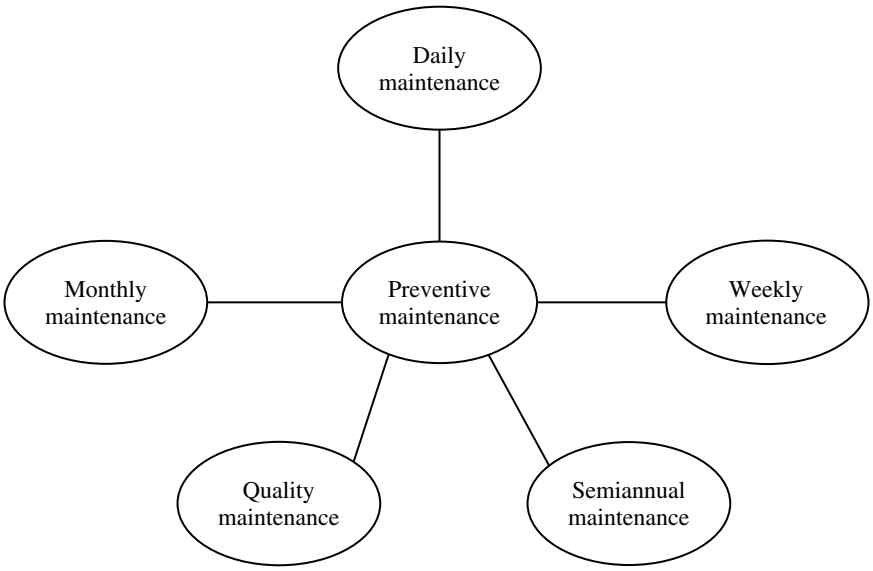

FIGURE 7.48 Periodicity of preventive maintenance. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

attention and the frequency for this attention. Accordingly, whenever possible, manufacturer's literature should be consulted before developing a schedule of maintenance for any pump. If the manufacturer's technical manual is not available, the manufacturer's representative should be consulted for assistance in developing a preventive maintenance schedule.

In cases where neither the manufacturer's technical manual or manufacturer's representative is available to assist you, the general preventive maintenance schedule, based on periodicity (see Figure 7.48), may be of assistance. (Note: It is important to point out that the idealized schedules, based on periodicity, presented in the following sections may be either too simple or too complex for any particular application. They are presented as a starting point for development of an overall preventive maintenance schedule. Each pumping situation may require this schedule to be modified or tailored to reflect on-site personnel experience and operating conditions.)

Note: The term preventive maintenance should not be assumed to be synonymous with another term that is commonly used today: predictive maintenance. Predictive maintenance is an advanced form of preventive maintenance. Predictive maintenance strategies seek to apply maintenance techniques only when needed, based on information such as vibration, thermographic and lubricant condition analyses.[30]

7.14.1 Daily Maintenance

For centrifugal pumps, the following observations, determinations, and adjustments should be made on a daily basis.

1. Visually observe pump operation.
2. Determine the approximate operating temperatures for motor, and bearings (by touch).
3. Adjust the seal water flow rate.
4. Adjust the packing gland.
5. Refill or adjust the oil or grease sealed packing gland.
6. Clean the sensor unit for pump control.
7. Check the foundation bolts.
8. Observe the motor operation.

7.14.2 Weekly Maintenance

For centrifugal pumps, the following observations, determinations, and adjustments should be made on a weekly basis.

1. Alternate operation. If two or more pumps of equal capacity are available, place second pump in operation.
2. Clean the pump. Lockout or tagout pump system and then remove all debris from inside the casing.
3. Check the packing assembly — If leaking excessively after tightening, remove packing and inspect shaft or shaft sleeve. If shaft or

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sleeve is badly grooved or extremely rough, make the necessary arrangements to have repairs made.

4. Check the operation of the control system. Is system starting the pump at the desired level and stopping the pump at the desired point? If not, clean and adjust.
5. Inspect the motor for indications of overload, burnt insulation, melted solder, etc. If any of these conditions are noted, have a qualified electrician inspect the motor.

7.14.3 Monthly Maintenance

For centrifugal pumps, the following observations, determinations, and adjustments should be made on a monthly basis.

1. Adjust the packing (if necessary).
2. Check the motor ventilation screens.

7.14.4 Quarterly Maintenance

For centrifugal pumps, the following observations, determinations, and adjustments should be made on a quarterly basis.

1. Inspect and lubricate the pump bearings. Drain lubricant and clean bearing with a solvent. Flush bearing housing and clean all moving parts. Inspect bearing seals and bearings for wear. Reassemble bearings and fill with the specified amount of the correct lubricant.
2. Check bearing temperature with a thermometer.

7.14.5 Semiannual Maintenance

For centrifugal pumps, the following observations, determinations, and adjustments should be made on a semiannual basis.

1. Check pump-motor shaft alignment.
2. Perform a complete inspection and servicing of pump.
   A. Determine pumping capacity.
   B. Determine pumping efficiency.
   C. Inspect wear rings.
   D. Inspect check valves and control valves.
   E. Clean scale and debris from pump casing.
   F. Inspect impeller condition and replace if worn.
   G. Inspect pump shaft and shaft sleeve and replace as required.

7.15 CENTRIFUGAL PUMP LUBRICATION

A centrifugal pump is made up of several parts that are designed to move at extremely high speeds. Lubrication of these moving parts is probably the most important and most frequently performed of all maintenance functions. Lubrication of centrifugal pump moving parts works to reduce friction and improve the efficiency of the pump. It is essential that these parts be lubricated. It is also important to note that in almost every case, too much lubrication can be as damaging as too little.

As is the case with other important centrifugal pump information, the manufacturer normally supplies specific lubrication information with each pump. This information is based upon the manufacturer's knowledge of the equipment, determined by controlled testing and actual field experience.

This section explains the purpose of lubrication, lubrication requirements, and lubrication procedures.

7.15.1 Purpose of Lubrication

Concerning centrifugal pumps, in this section we discuss the benefits of lubrication as illustrated in Figure 7.49.

7.15.1.1 Separates Surfaces

To reduce friction between moving parts, a thin film of lubricant must separate them. All lubricants, no matter their type, have the ability to separate surfaces. The lubricant's formulation determines the degree (amount) of separation between the parts. Lubricants can be grease, oil, or compressed air or other gas.

7.15.1.2 Prevents Wear

When a lubricant's film layer separates moving parts, it also reduces the amount of wear that takes place as the surfaces rub against one another. The equation is quite simple: reduced wear = longer life expectancy. Moreover, as wear does occur (because of the speed of the machine and environmental factors), the lubricant film limits the amount of clearance that occurs as the wear takes place.

7.15.1.3 Cushions Shock

Lubricants provide a cushion between moving parts that dampens shock. The degree of shock dampening provided depends on the lubricant's characteristics and the surfaces it separates. For example, a heavy lubricant, such as grease, is better suited for separating the surfaces and absorbing the shock. The downside of using heavy lubricants, however, is that they do not flow as easily as liquids. Accordingly, when the moving parts are subjected to high speeds, oil bath-type lubrication is required.

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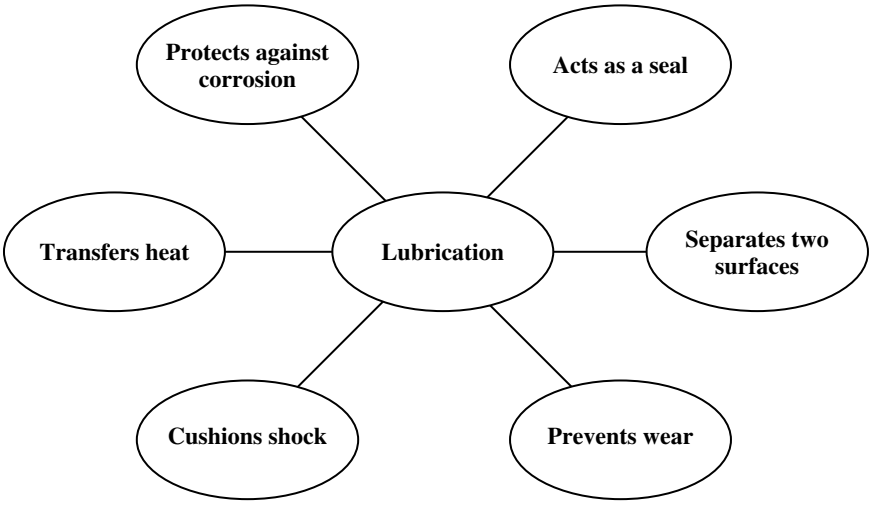

FIGURE 7.49 Benefits of lubrication. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.15.1.4 Transfers Heat

Many maintenance operators have the misconception that lubricants function to absorb heat, and thus protect machinery. Lubricants do absorb a limited amount of heat, but they actually work to transfer the heat. If lubricants are subjected to too much heat, they break down. This is the reason that many lubricating systems are water-cooled. Water is an excellent cooling agent.

7.15.1.5 Corrosion Protection

One of the major enemies of any metal surface is corrosion. Once the metal surface of most parts is exposed to the elements, corrosion is the result. However, lubricants coat surfaces and work to reduce corrosion. Most lubricants are formulated with corrosion inhibitors and other chemical additives that improve their film consistency and limit corrosion from occurring.

7.15.1.6 Protective Seal

Depending on the consistency and application of the lubricant, lubrication can provide an excellent protective seal from contamination and moisture.

7.15.2 Lubrication Requirements

Whenever lubrication is used, there are several basic requirements that should be kept in mind:

1. The lubricant should be of the type specified by the manufacturer. If a different brand of lubricant is used, it should be specified as equivalent to the recommended brand.
2. Only high quality lubricants should be used.
3. Lubricants should be added in the amounts and methods specified by the manufacturer. In certain cases, the lubricant is added with the equipment operating, in other cases, the equipment should be idle. Failure to observe the manufacturer's recommendations can result in damage to the bearings or lubrication seals.
4. The lubricant must reach the desired point of application to be effective. If the grease fitting is plugged or, in the case of lubricant lines for bearings on extended shafts, the line is broken or disconnected, the lubricant will do no good. It is best to inspect lubrication systems frequently to ensure they are working properly.
5. Lubrication responsibility must be assigned to a specific employee to be effective. If left to anyone to accomplish, it is likely that the lubrication will be given a low priority and may not be done as scheduled; it may also be a recipe for pump failure. The person assigned to perform the lubrication should know how to do it properly.
6. Lubrication systems must be accessible. If it is difficult or hazardous to reach a grease fitting or an oil cup, it is unlikely that anyone is going to be eager to perform the lubrication.
7. In many cases, lubrication may require special equipment or tools. If lubrication is to be performed, these must be readily available.

7.15.3 Lubrication Procedures

Specific lubrication schedules and procedures will vary from one manufacturer to another. As stated earlier, the best source of information regarding the lubrication of individual pumps is the manufacturer. In many cases, plant

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maintenance operators have found it necessary to modify these recommendations based upon their own experience and the specific application of the pump. For this reason, the procedures provided in this handbook are general, idealized procedures that must be reviewed and modified to meet the specific requirements of each individual application.

Note: Proper lubrication means not only regular lubrication, but use of the proper lubricant in the proper amount.

7.15.3.1 Motor Bearing Lubrication

Bearings are a primary part of a motor. In order to operate correctly, bearings must be lubricated with the proper kind of lubricating material in the correct amount. This section provides an idealized motor bearing lubrication procedure.

Note: Proper lubrication of motor bearings is extremely important. Without proper lubrication, bearings will overheat, rust, corrode, and eventually cause the shaft to seize and stop. If a motor has been shut down for a long period without proper lubrication, the bearings can become so rusted that the motor will be unable to turn the pump shaft.

7.15.3.1.1 Motor Bearing Lubrication Procedure

1. Check to determine if the motor bearings require lubrication. Many newer motor bearings are composed of metals that are impregnated with lubricant. These bearings do not normally require any additional lubrication. If this type of bearing is used, normally there are no lubrication fittings located on the bearing assembly.
2. Remove relief plug from bearing assembly (normally located on the opposite side from the grease fitting).
3. Remove any hardened grease from the relief plug and clean the grease fitting.
4. With the motor running, add four to five strokes of the grease gun to the grease fitting. If the bearing does not have a relief plug, then the new grease should be added very slowly to prevent damage to the bearing's seals.
5. Allow the fresh grease to be heated by running the motor for 5 to 10 minutes. Leave the relief plug out during this time so that excess grease may drain out of the bearing assembly.
6. Replace the relief plug and note the date of the lubrication in the maintenance records.

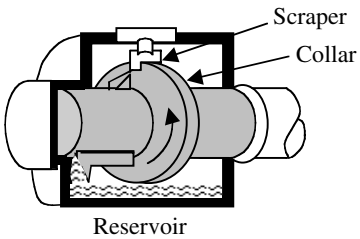

FIGURE 7.50 Slinger ring oiler. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.15.3.2 Pump Bearing Lubrication

Pump bearings may be grease or oil lubricated depending on the manufacturer or supplier's preference. Some special applications use synthetic lubricants. Horizontally shafted pumps may use either oil or grease lubrication; the vertically shafted pump will normally use grease lubrication because of the difficulties that arise when trying to provide a seal that will prevent the loss of the lubricant. Systems to prevent loss of grease are more readily available and more efficient than those for oil are. Although it is more difficult to use oil lubricated bearings on vertically shafted pumps, there are many cases where they are used.

Note: The type of lubricant used depends upon the pump application and the manufacturer's instructions. If, for example, the pump is operated outdoors in changing temperatures, oil will perform better than grease because its lubricating qualities are not affected by changing temperatures.

7.15.3.2.1 Oil Lubrication of Pump Bearings

Oil lubrication of pump bearings is widely used for light-to-moderate high-speed horizontally shafted pumps. The design of the oil lubrication system allows oil to be sprayed over the bearing through the use of a slinger ring (see Figure 7.50); the movement of the bearing through the oil reservoir; or, in some cases, the use of an external system that sprays the oil over the bearing.

Note: It is essential that the bearing be coated with a very thin film of oil to provide lubrication without restricting the movement of the bearing. This would increase the operating temperature of the bearing and decrease its operating life.

7.15.3.2.2 Oil Selection

The oils used for bearing lubrication should be filtered, nondetergent mineral oils of grades SAE 10 or 20 without corrosive or abrasive components. Animal or vegetable oils should be avoided, because of the acids formed as these oils break down. The oils selected for use must be capable of providing adequate lubrication at start-up and at the normal operating temperature of the bearing. If the

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manufacturer's recommendations are not available, the operating temperature of the bearing and the operating conditions should be discussed with a lubrication specialist to determine the best oil for use.

7.15.3.2.3 Oiling Procedure

The normal procedure for oiling pump bearings is a relatively simple matter of draining the oil and refilling the bearing lubrication reservoir with fresh oil.

1. If there is indication that the bearing has been contaminated, it may be necessary to flush the bearing with a suitable solvent. After flushing with solvent, the bearing should be flushed with clean oil to remove excess solvent.
2. The oil reservoir should then be filled to the appropriate level with fresh oil.
3. In some cases, the bearing receives oil lubrication from an external source such as a reservoir or an automatic oiler. In these cases, daily operation must include checking the delivery of the lubrication to the bearing and refilling the oil reservoir.

7.15.3.2.4 Grease Lubrication of Pump Bearings

Grease lubrication of pump bearings is widely used for heavy loads at low to moderate shaft speeds and for vertically shafted pumps where it would be difficult to maintain the necessary reservoir of oil for the bearing. The use of grease allows the lubricant to be placed where it is needed without the need for sophisticated seals to prevent leakage.

Note: As a general rule, pumps should be greased about every 3 months.

7.15.3.2.5 Grease Selection

Grease lubricants for pump bearings are normally designed to provide oil lubricant in a soap-like base. This allows the oil to liquefy near the surface of the moving parts to provide a light film of lubricant.

Note: When grease is used in a pump application, check its grade and consistency to make sure that it is the type specified by the pump manufacturer.

Temperature is a major consideration in selection of the grease; if the pump operates in an environment with a high ambient temperature, a grease with a high melting point should be selected. Major strides have been made in developing multipurpose grease that can be used over a wide range of temperatures and applications. However, there are many bearing manufacturers that still recommend the use of specific soap greases because of the highly dependable nature of these lubricants and the long history of dependable use.

The two most widely used forms of soap-based lubricants are the lime soap base and soda-based greases. It is very important that the correct base be selected since the base is a critical factor in the degree of lubrication obtained at any specific operating temperature. If the lubricant is too soft, it will flow into the open spaces between the moving parts. If these spaces become filled, the resistance to movement (friction) will cause excessive wear. If the grease is too stiff, the grease will freeze the moving parts of the bearing. This will make the start-up more difficult and may cause excessive wear during start-up.

7.15.3.2.6 Greasing Procedure

The greasing procedure for pump bearings follows the same basic procedure outlined for greasing motor bearings. Depending upon the severity of use and operating conditions, the lubrication schedule may be as frequent as every 1 to 3 months (continuous operation) or as little as every 6 to 9 months for pumps that are not operated frequently. It should be noted that under some conditions, it might be necessary to lubricate more frequently. Manufacturer's recommendations and experience must be used to determine the best lubrication schedule.

Note: Like excessive oiling, excessive greasing is just as detrimental as too little lubrication and can cause much damage. In addition to generating heat, an excessive amount of grease can rupture lubricant seals. Ruptured seals can allow contaminants to enter the bearing, causing bearing failure.

7.16 CENTRIFUGAL PUMP: TROUBLESHOOTING

Throughout our discussion of centrifugal pumps, we have pointed out repeatedly that their capability to provide reliable and trouble-free operation. However, as with any other piece of mechanical equipment, problems do develop. Whether the problem is the result of poor design or installation techniques or the lack of routine maintenance, time and money are lost each time a pump goes down.

This section discusses the troubleshooting procedures for 13 common symptoms related to centrifugal pump problems. In addition, we provide information designed to assist the maintenance operator determine the possible causes and remedies for centrifugal pump problems. The best source of troubleshooting information is the pump manufacturer. The troubleshooting suggestions and the charts provided by the manufacturer often make it possible for operators to identify a problem and correct it on their own.

7.16.1 The Troubleshooter[31]

Few would argue that in order to paint an artistic masterpiece along the lines (or to similar standards) of the great

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masters like Da Vinci, Raphael, and others, a certain amount of artistic skill is not only involved, but is also required. The same can be said for the bridge builder, the house builder, the car manufacturer, and many other types of builders; in a sense, they are all artisans.

The same can be said for the troubleshooter. While troubleshooting is an art, it is also a skill. The difference between the natural ability of the artist and the skill of the troubleshooter is that the ability to perform correct, accurate troubleshooting can be learned or taught — even those who are not necessarily naturally artistic can master it.

Troubleshooting is defined as the art or science of problem solving. Some would simplify this by stating that troubleshooting is a simple, systematic method to identify and correct problems. This may be the case, but experience has shown that nothing is simple and systematic unless a certain amount of experience is thrown into the equation.

Another trait needed is common sense. Operators may get by (to a degree) in troubleshooting with a lack of expertise, experience, or a simplistic and systematic approach — but you can't get by without a great deal of common sense.

Consider the technical student who spends several years in formal classroom training to become an electrician. This student may have little difficulty in understanding Ohm's law, AC/DC theory, inductance and capacitance, Boolean algebra, logic circuits, and even more complex electrical theory. This same student may ace these subjects and the course. But does the ability to score high on theoretical concepts translate to a high degree of proficiency in troubleshooting an electronic or electrical circuit?

It depends on experience. As the old adage says, "There simply is no substitute for experience."

If this same brilliant student is exposed to real life, on-the-job situations where he has to troubleshoot complicated systems and solve problems, he will learn over time. If you add the student's high degree of common sense (assuming he has this nebulous gift) to this learning experience, then he will learn more easily and quickly and retain what he has learned.

7.16.2 Troubleshooting: What Is It?

Troubleshooting is the art of problem solving (sound familiar?). More specifically, troubleshooting provides a mechanism or means to address problems and evaluate possible solutions. It is important to remember that no machine, electrical circuit, or water or wastewater treatment plant unit process runs at maximum efficiency at all times. In fact, in both water and wastewater treatment, unit process problems are not uncommon. Some of the problems are due to poor design or unusual raw water or influent characteristics. One thing is absolutely certain — the majority of treatment plant problems are avoidable by practicing better operation, management, maintenance, and process control.

To achieve optimum operation and control, the operator must be able to rapidly identify problems. More importantly, once identified, the problems must be corrected. Maintaining optimum performance of any system, including centrifugal pumps, requires the ability to troubleshoot and do it correctly.

Note: Due to the complexity of treatment systems, unit processes, machinery and equipment (e.g., centrifugal pumping systems), and the number of variables involved, troubleshooting may not always identify one single right answer. The process requires experience, time, common sense, and usually a good deal of effort to solve performance problems. Probably the most important factor in troubleshooting is system knowledge. Simply put, you cannot determine what the solution to a problem is with most complex processes, systems, or equipment unless you understand the operation of the process, system, or equipment. To remedy any difficulties experienced, the operator must know the characteristics of the system or wastestream; the design shortcomings of the process, system, or equipment; and the indicators of operational problems.

7.16.3 Goals of Troubleshooting

There are many different reasons for troubleshooting a centrifugal pump. The reasons vary from developing procedures to prevent future problems, to improving overall plant performance, and to reducing operation and maintenance costs. However, probably the most common reason (most important reason) for identifying and correcting a problem is when the problem causes the plant to operate at a below optimum level that may lead to a permit violation. Centrifugal pumps are part of the treatment process; when they are not operating as designed, they can and will affect process operations. As an aside, it is important to remember that centrifugal pumps may run for years without problems, but some may exhibit problems as soon as start-up occurs.

7.16.4 The Troubleshooting Process

Note: There is no one perfect method for troubleshooting treatment process problems; each situation can (and probably will) vary. However, there are certain steps or elements in the process of troubleshooting that should be followed each time — these are listed in this section. Keep in mind that these common elements apply to almost all troubleshooting applications, and not just to equipment such as centrifugal pumps.

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The common elements in successful troubleshooting approaches include:

1. Observe and gather information — To begin the correct troubleshooting process or approach, there is a need to understand what is or is not happening with the process. It does not work. Okay, what does that mean? What does not work or what does not work correctly? These questions must be asked first, before any corrective action is attempted. Follow the old adage, "Look before you leap."
2. Identify additional data needed — Many wastewater treatment systems or unit processes are quite complex. Simply because one element of the process has been identified as nonfunctional does not necessarily mean that it is the causal factor of the overall malfunction. Many times failure of one component is caused by failure of some other device or system downstream or upstream of the component not functioning as designed. Collect all the information, not just patchwork details.
3. Evaluate available information — After all the data and information are collected, the next step is to evaluate what it is that you know.
4. Identify potential problems, causes, and corrective actions — With the proper information in hand, the next step is to look at each potential causal factor. Next, through process of elimination, narrow down the causes and corrective actions.
5. Prioritize problems, causes and corrective actions — After the potential causes and corrective actions are narrowed down to a small list, prioritize them.
6. Select the actions to be taken — A short list of actions to take should be made to determine if any of them are the corrective actions required.
7. Implement — Starting with the most likely corrective action, implement it first and then proceed down the list until the problem is remedied. (Note: if the problem is not remedied from the corrective actions listed, then the process needs to start over from the beginning).
8. Observe the results — After the selected remedial action is effected, observing the impact of the action is important.
9. Documenting (record keeping) for future use — One thing is certain: If a system or unit process fails once, it is quite likely that it will fail again. If this is the case (and it is), why would anyone want to spend an inordinate amount of time and effort finally determining the causal factor without taking the time to document it? Local knowledge is important in maintaining the smooth, uninterrupted operation of a water or wastewater treatment plant; local troubleshooting knowledge is more than important, it is critical.

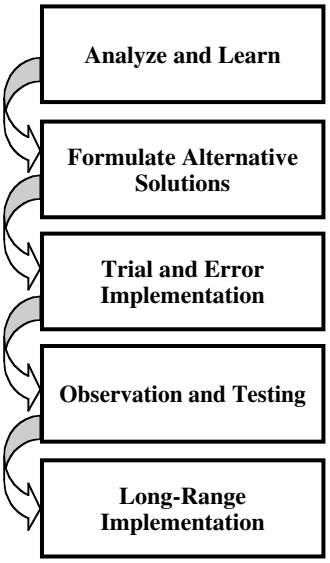

FIGURE 7.51 Simplified troubleshooting steps. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

A simplified basic summary of the elements listed above is shown in Figure 7.51. Figure 7.52 shows a more detailed step-by-step troubleshooting process. It is a model or paradigm that has one huge advantage over many others: it has been tested.

7.16.5 Troubleshooting the Centrifugal Pump

We stated earlier that anyone attempting to troubleshoot a system, process, or piece of equipment without first knowing its basic operation is performing a foolhardy exercise at best. Accordingly, the maintenance operators (the troubleshooter) must know the characteristics, design shortcomings, and indicators of operational problems for the centrifugal pump they are attempting to troubleshoot.

In the following sections, we provide 11 typical problems associated with centrifugal pumps. Along with the problem or symptom, we also provide possible causes and the required action or remedy.

Note: Again, it is important to remember that the manufacturer's technical manual for the centrifugal pump is the resource that should be used in troubleshooting a centrifugal pump. Moreover, only experienced maintenance operators should perform the actual troubleshooting process.

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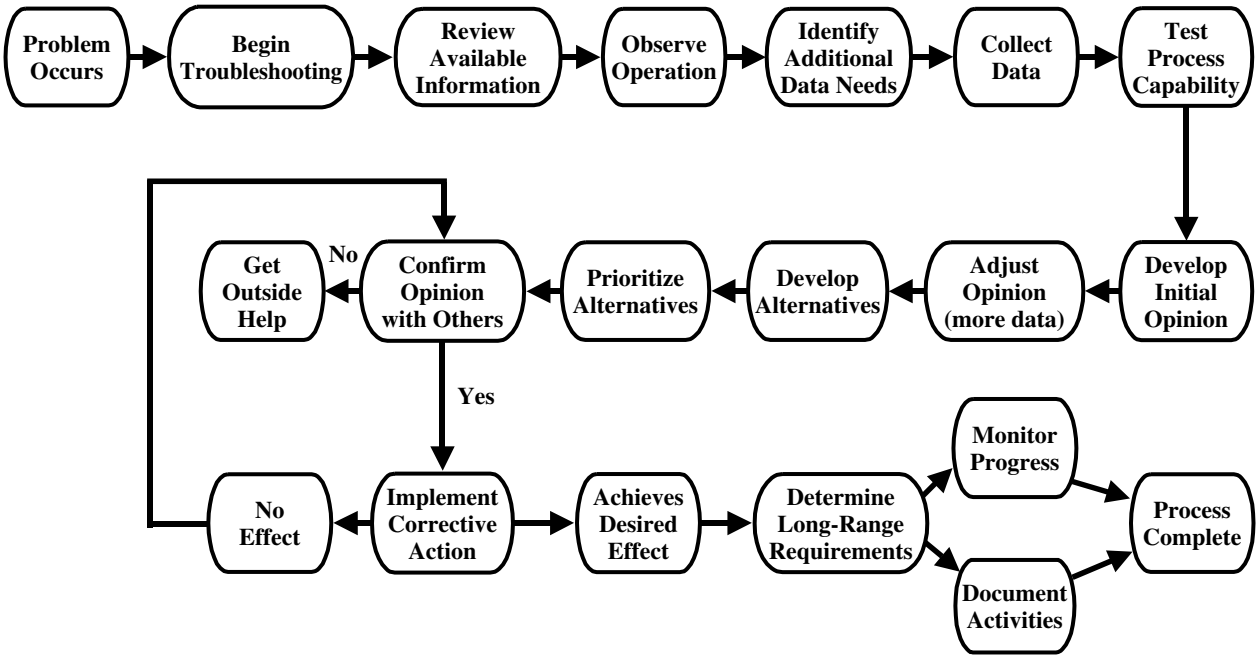

FIGURE 7.52 Troubleshooting sequence. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.16.5.1 Pump Fails to Prime or Loses its Prime

Possible Cause:

1. Air leaks in suction line.
2. Suction strainer or inlet is clogged.
3. Suction lift is too high.
4. Defective priming unit.
5. Defective packing or seal causing air leakage.
6. Excessive air or vapor in liquid.
7. Air pocket in suction line
8. Air leaks into pump through gaskets.
9. Inlet or suction line is improperly located.
10. Lantern ring is improperly located.
11. Water seal pipe is plugged.

Action or Remedy:

1. Inspect, clean, and tighten all suction connections.
2. Remove dirt, leaves, or other material from strainer or inlet.
3. Reevaluate pump requirements and correct suction conditions accordingly.
4. Inspect, clean, and repair priming unit; replace any defective parts.
5. Inspect packing or seal for proper operation. Listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring.
6. Visually observe liquid being pumped for evidence of excessive air or vapor concentrations.
7. Open air bleed-off valves in suction piping or on pump; listen for excessive noise in suction lines.
8. Visually inspect the pump's gasket and O-ring locations for signs of cracks or deterioration; feel around these locations for signs of air leakage.
9. Reevaluate suction line configurations and determine if they need to be relocated or modified.
10. Consult manufacturer's literature and inspect stuffing box to ensure proper location of packing and lantern ring.
11. Inspect external water seal unit. Remove piping at pump end to ensure water is flowing and inspect connection at the stuffing box.

7.16.5.2 Pump Does Not Discharge

Possible Cause:

1. Pump is not properly primed.
2. Total head is too high.
3. Drive unit is not operating at rated speed.
4. Impeller or discharge line is clogged.
5. Suction or discharge check or line valves are closed.
6. Wrong direction of rotation.
7. Pump is vapor bound.
8. Suction line location problems.
9. Suction lift is too high.
10. Air leaks in pump or suction piping.

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Action or Remedy:

1. Reprime the pump. Refer to priming troubleshooting and remedies.
2. Reevaluate head calculations. Measure elevation differences between the pump and liquid source and the pump and discharge points. Check pipe friction losses. Are valves wide open?
3. Check voltage of electric motor. Check steam pressure of steam turbine. Check engine r/min. Refer to applicable maintenance manuals for possible troubles and corrective action.
4. Backflush pump to try to clear obstruction. Remove pump inspection plate (if so equipped) and clean impeller. Dismantle pump or piping and remove obstruction.
5. Check all suction and discharge line valves associated with the pump to ensure proper positioning; inspect and operate check valves to ensure proper operation.
6. Observe pump rotation and compare with indicator arrow. Check wiring against diagram on motor name plate and in controller. Consult manufacturer's literature for troubleshooting procedures. Acquire the services of a qualified electrician to perform needed repairs.
7. Provide additional pressure on liquid being pumped by elevating liquid level. Bleed excess air from pump and suction piping.
8. Reevaluate suction line configurations and determine if they need to be relocated or modified.
9. Reevaluate pump requirements and correct suction conditions accordingly.
10. Inspect, clean, and tighten all suction connections. Inspect packing or seal for proper operation. Listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring. Visually inspect the pump's gasket and O-ring locations for signs of cracks or deterioration, and feel around these locations for signs of air leakage

7.16.5.3 Pump Does Not Deliver Rated Capacity

Possible Cause:

1. Pump is not properly primed.
2. Suction lift is too high.
3. Excessive air or vapor in liquid.
4. Air leaking through stuffing box, suction line, or pump casing.
5. Drive unit is not operating at rated speed.
6. Impeller is clogged.
7. Wear rings are worn.
8. Impeller is damaged or eroded.
9. Pump is vapor bound.
10. Discharge pressure required by the system is greater than that for which the pump was designed.
11. Insufficient suction head (cavitation occurring).
12. Foot valve too small or clogged.
13. Vortexing.
14. Air pocket is in suction line.
15. Water seal pipe is plugged.

Action or Remedy:

1. Reprime the pump. Refer to priming troubleshooting and remedies.
2. Reevaluate pump requirements and correct suction conditions accordingly.
3. Inspect packing or seal for proper operation. Listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring.
4. Visually observe liquid being pumped for evidence of excessive air or vapor concentrations. Inspect, clean, and tighten all suction connections. Visually inspect the pump's gasket and O-ring locations for signs of cracks or deterioration. Feel around these locations for signs of air leakage
5. Check voltage of electric motor. Check steam pressure of steam turbine. Check engine r/min. Refer to applicable maintenance manuals for possible troubles and corrective action.
6. Backflush pump to try to clear obstruction. Remove pump inspection plate (if so equipped) and clean impeller; dismantle pump and/or piping and remove obstruction
7. Inspect pump wear rings for excessive wear. Measure clearances, and if they are out of the acceptable range, replace the wear rings.
8. Remove pump inspection plate (if so equipped) or disassemble pump and inspect impeller. If it is damaged or eroded, replace the impeller.
9. Provide additional pressure on liquid being pumped by elevating liquid level. Bleed excess air from pump and suction piping.
10. Reevaluate pumping system requirements and make the necessary modifications or changes.
11. Increase the liquid level in the pumped tank. Reevaluate the design of the suction portion of the pumping system.
12. Inspect the foot valve. The free area through all parts of the valve should be no less than 1.5 times the area of the suction pipe. If a strainer is used, area should be three or four times the area of the suction pipe

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13. Increase the liquid level in the pumped tank. Reevaluate the design of the suction portion of the pumping system.
14. Open air bleed-off valves in suction piping or on pump. Listen for excessive noise in suction lines.
15. Inspect external water seal unit; remove piping at pump end to ensure water is flowing and inspect connection at the stuffing box.

7.16.5.4 Pump Does Not Deliver Sufficient Pressure

Possible Cause:

1. Excessive air or vapor in liquid.
2. Drive unit is not operating at rated speed.
3. Wrong direction of rotation.
4. Total head is too high.
5. Wear rings are worn.
6. Impeller is damaged or eroded.
7. Air leaks through pump or suction lines.
8. Suction or discharge valves are partially opened.
9. Suction or discharge lines are partially clogged.
10. Impeller size is not correct.

Action or Remedy:

1. Visually observe liquid being pumped for evidence of excessive air or vapor concentrations.
2. Check voltage of electric motor. Check steam pressure of steam turbine. Check engine r/min. Refer to applicable maintenance manuals for possible troubles and corrective action.
3. Observe pump rotation and compare with indicator arrow. Check wiring against diagram on motor name plate and in controller. Consult manufacturer's literature for troubleshooting procedures. Acquire the services of a qualified electrician to perform needed repairs.
4. Reevaluate head calculations. Measure elevation differences between the pump and liquid source and the pump and discharge points. Check pipe friction losses. Are valves wide open?
5. Inspect pump wear rings for excessive wear. Measure clearances, and if they are out of the acceptable range, replace the wear rings
6. Remove pump inspection plate (if so equipped) or disassemble pump and inspect impeller. If damaged or eroded, replace the impeller
7. Inspect, clean, and tighten all suction connections. Inspect packing or seal for proper operation. Listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring. Visually inspect the pump's gasket and O-ring locations for signs of cracks or deterioration, and feel around these locations for signs of air leakage.
8. Check all suction and discharge line valves associated with the pump to ensure proper positioning. Inspect and operate check valves to ensure proper operation.
9. Remove dirt, leaves, or other material from strainer or inlet and backflush the pump if possible; if not, dismantle the pump and remove any obstructions.
10. Check actual diameter of impeller. Consult with pump manufacturer to see if impeller needs to be replaced.

7.16.5.5 Pump Starts and Stops Pumping

Possible Cause:

1. Air leaks through pump or suction lines.
2. Air pocket is in suction line.
3. Excessive air or vapor is in liquid.
4. Water seal pipe or line is plugged.
5. Suction lift is too high.
6. Defective packing or mechanical seal.
7. Pump vapor bound.
8. Pump was not properly primed.
9. Casing distorted by excessive strains from suction or discharge piping.
10. Shaft bent due to thermal distortion, damage during overhaul, or improper assembly of rotating elements.
11. Mechanical failure of critical pump parts.

Action or Remedy:

1. Inspect, clean, and tighten all suction connections. Inspect packing or seal for proper operation; listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring; Visually inspect the pump's gasket and O-ring locations for signs of cracks or deterioration, and feel around these locations for signs of air leakage.
2. Open air bleed-off valves in suction piping or on pump; listen for excessive noise in suction lines.
3. Visually observe liquid being pumped for evidence of excessive air or vapor concentrations.
4. Inspect external water seal unit; remove piping at pump end to ensure water is flowing and inspect connection at the stuffing box.
5. Reevaluate pump requirements and correct suction conditions accordingly.

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6. Inspect packing or seal for proper operation. Listen and feel for evidence of air leaking into pump through the stuffing box. Check shaft and its sleeve for scoring.
7. Provide additional pressure on liquid being pumped by elevating liquid level; bleed excess air from pump and suction piping.
8. Reprime the pump. Refer to priming troubleshooting and remedies.
9. Inspect interior of pump for friction and wear between impeller and casing; replace damaged parts and eliminate piping strains.
10. Check shaft deflection by turning between lathe centers. Shaft warpage should not exceed 0.002 in. on any pump.
11. Inspect bearings and impeller for damage. Any irregularity on the parts will cause a drag on the shaft and improper operation.

7.16.5.6 Pump Overloads Driver or Consumes Excessive Power

Possible Cause:

1. Motor speed is too high.
2. Wrong direction of rotation.
3. Total head is too high.
4. Total head is too low.
5. Impeller is clogged.
6. Impeller size is not correct.
7. Motor shaft is bent.
8. Drive unit and pump are misaligned.
9. Wear rings are worn.
10. Packing is improperly installed.
11. Rotating and stationary parts are rubbing.

Action or Remedy:

1. Internal electric motor wiring is incorrect. Replace motor. Refer to applicable drive unit maintenance manuals for possible troubles and corrective action.
2. Observe pump rotation and compare with indicator arrow. Check wiring against diagram on motor name plate and in controller. Consult manufacturer's literature for troubleshooting procedures. Acquire the services of a qualified electrician to perform needed repairs.
3. Reevaluate head calculations. Measure elevation differences between the pump and liquid source and the pump and discharge points. Check pipe friction losses. Are valves wide open?
4. Reevaluate head conditions. Correct as required
5. Backflush pump to try to clear obstruction. Remove pump inspection plate (if so equipped) and clean impeller, Dismantle pump or piping and remove obstruction.
6. Check actual diameter of impeller. Consult with pump manufacturer to see if impeller needs to be replaced.
7. Inspect motor shaft. Replace shaft if it is bent.
8. Inspect shafts and couplings for angular and parallel misalignment. If out of alignment, correct the misalignment
9. Inspect pump wear rings for excessive wear. Measure clearances, and if they are out of the acceptable range, replace the wear rings.
10. Remove packing. Inspect and reinstall correctly. Replace packing if necessary.
11. Rotate pump by hand, listening and feeling for rubbing parts. If impeller is binding, realign or relieve strain on casing. Adjust impeller clearance. Replace worn or damaged parts.

7.16.5.7 Pump Is Noisy or Has Extensive Vibration

Possible Cause:

1. Magnetic hum.
2. Motor bearings are worn.
3. Impeller is clogged.
4. Impeller is binding.
5. Motor shaft is bent or worn.
6. Drive and pump are misaligned.
7. Foundation is not rigid.
8. Impeller is damaged.
9. Pump is not properly leveled.
10. Piping is not supported.
11. Pump is cavitating.
12. Pump or suction pipe is not completely filled with liquid.
13. Foot valve is too small or partially clogged.
14. Pump shaft is bent.
15. Excessive lubrication in motor and pump ball bearings.
16. Lack of lubrication in motor and pump ball bearings.
17. Internal misalignment due to worn bearings.

Action or Remedy:

1. Consult motor manufacturer's technical manual.
2. Replace bearings.
3. Backflush pump to try to clear obstruction. Remove pump inspection plate (if so equipped) and clean impeller. Dismantle pump or piping and remove obstruction.
4. Rotate pump by hand, listening and feeling for rubbing parts. If the impeller is binding, realign

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or relieve strain on casing. Adjust impeller clearance. Replace worn or damaged parts.

5. Inspect motor shaft. Replace shaft if it is bent.
6. Inspect shafts and couplings for angular and parallel misalignment. If they are out of alignment, correct the misalignment.
7. Inspect foundation. Strengthen or change method of mounting pump unit.
8. Remove pump inspection plate (if so equipped) or disassemble pump and inspect impeller. If damaged or eroded, replace the impeller.
9. Check levelness of pump. Make necessary changes to relevel the pump. Recheck shaft alignments.
10. Provide support for suction and discharge piping.
11. Inspect pump impeller casing for signs of cavitation. If present, reevaluate pump application and suction and discharge piping. Consult with pump manufacturer
12. Open air purges on suction line and pump. Reevaluate suction piping and pump location. Modify system as needed.
13. Inspect the foot valve. Free area through all parts of the valve should be no less than 1.5 times the area of the suction pipe. If a strainer is used, area should be three or four times the area of the suction pipe.
14. Inspect bearings and impeller for damage. Any irregularity on the parts will cause a drag on the shaft and improper operation.
15. Inspect bearings. Clean with solvent and relubricate properly. Replace if damaged.
16. Inspect bearings. Clean with solvent and relubricate properly. Replace if damaged.
17. Replace bearings.

7.16.5.8 Packing Has a Short Life

Possible Cause:

1. Water seal pipe is plugged or no water is being provided.
2. Seal cage is improperly located.
3. Packing is improperly installed.
4. Incorrect packing for operating conditions.
5. Packing gland is too tight
6. Dirt or grit is in sealing liquid.
7. Shaft misalignment.
8. Shaft is bent.
9. Bearings are worn.
10. Shaft sleeve is worn or scored.

Action or Remedy:

1. Inspect external water seal unit; remove piping at pump end to ensure water is flowing and inspect connection at the stuffing box.
2. Consult manufacturer's literature and inspect stuffing box to ensure proper location of packing and lantern ring.
3. Remove packing. Inspect and reinstall correctly. Replace packing if necessary
4. Consult with manufacturer's representative or read literature and select the proper packing.
5. Remove gland and packing. Repack the pump and follow the recommended procedures for adjusting the gland.
6. Add filters to the sealing liquid line. Use a clean water source for sealing liquid.
7. Inspect shafts and couplings for angular and parallel misalignment. If they are out of alignment, correct the misalignment.
8. Inspect motor shaft. Replace shaft if it is bent
9. Replace the bearings.
10. Remove gland and packing and inspect shaft sleeve for wear. This generally has to be done by hand or with a packing tool.

7.16.5.9 Mechanical Seal Has a Short Life

Possible Causes:

1. Shaft is bent.
2. Shaft sleeve is worn or scored.
3. Seal is improperly installed.
4. Improper seal for operating conditions.
5. Abrasive solids in liquid are being pumped.
6. Mechanical seal was run dry.
7. Bearings are worn.
8. Pump shaft misalignment.

Action or Remedy:

1. Inspect motor shaft. Replace shaft if it is bent.
2. Remove gland and packing and inspect shaft sleeve for wear. This generally has to be done by hand or with a packing tool.
3. Remove seal. Consult with manufacturer's representative and read instructions with seal. Reinstall seal following proper instructions.
4. Consult with manufacturer's representative and choose proper seal for application.
5. Provide a separate clean seal water source.
6. Operate the pump only while seal water is flowing.

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7. Replace the bearings
8. Inspect shaft for damage due to misalignment. Replace if damaged. Correct the problem causing misalignment (worn bearings, out of balance impeller, pipe strain, etc.).

7.16.5.10 Mechanical Seal Leaks Excessively

Possible Cause:

1. Leakage under shaft sleeve due to gasket or O–ring failure

Action or Remedy:

1. Determine if leakage is actually between shaft sleeve and shaft. Replace gasket or O-ring.
2. Inspect motor shaft. Replace shaft if it is bent.
3. Remove gland and packing and inspect shaft sleeve for wear. This generally has to be done by hand or with a packing tool.
4. Remove seal. Consult with manufacturer's representative and read instructions with seal. Reinstall seal following proper instructions.
5. Consult with manufacturer's representative and choose proper seal for application.
6. Provide a separate clean seal water source.
7. Operate pump only while seal water is flowing.
8. Replace the bearings.
9. Inspect shaft for damage due to misalignment. Replace if damaged. Correct the problem causing misalignment (worn bearings, out of balance impeller, pipe strain, etc.).

7.16.5.11 Bearings Have a Short Life

Possible Cause:

1. Shaft is bent or damaged.
2. Excessive thrust caused by a mechanical failure inside the pump.
3. Excessive grease in bearings.
4. Lack of lubrication in bearings.
5. Rusting of bearings due to water getting into bearings past slinger ring.
6. Out of balanced shaft or impeller.

Action or Remedy:

1. Check shaft deflection by turning between lathe centers. Shaft warpage should not exceed 0.002 in. on any pump.
2. Dismantle pump and determine the extent of the damage. If capable and the right tools are available, repair internal damage.
3. Replace bearing. Relubricate following accepted procedures.
4. Replace bearing. Lubricate following accepted procedure.
5. Replace and relubricate damaged bearing. Replace or repair slinger ring.
6. Replace shaft or impeller.

7.16.5.12 Pump Overheats or Seizes

Possible Cause:

1. Pump is not primed and allowed to run dry.
2. Vapor or air pockets inside of pump.
3. Operation at too low capacity.
4. Internal misalignment due to improper repairs.
5. Rubbing or rotating and stationary parts.
6. Bearings are worn.
7. Lack of lubrication.

Action or Remedy:

1. Check bearing temperature and try to turn pump by hand. If the pump turns freely, try repriming pump again. If it does not turn freely, inspect the pump for impeller damage, bent shaft, and seized bearings.
2. Shut the pump down. Check the bearing housing and volute case for excessive temperature conditions. Turn the pump by hand. If the pump turns freely, start the pump and open the air release plugs to allow entrapped air out. If the pump does not turn freely inspect pump impeller, shaft, volute, and bearings for damage.
3. Reevaluate pump system operating conditions; consult with pump supplier for corrective actions.
4. Shut the pump down. Turn pump by hand. If pump does not turn freely or drags, inspect pump impeller, shaft, and wear rings for damage. Have a competent repairman service the pump.
5. Replace the bearings.
6. Shut the pump down. Check bearing temperature. Turn the pump by hand. If the pump turns freely, relubricate the bearings according to lubrication instructions and follow a prescribed lubrication schedule in the future. If the pump has seized replace and lubricate bearings, turn the pump by hand once again to ensure it is ready to run.

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7.17 CENTRIFUGAL PUMP MODIFICATIONS

The centrifugal pump (and its modifications) is one of the most diversified hydraulic machines used in water and wastewater treatment. Along with its reliability and other advantages, the centrifugal pump can also be used in a wide range of different applications.

The centrifugal pump's wide diversity in application is the result of its adaptability through various modifications. These modifications include variations in impeller design, including the use of semi-open, open, or closed impellers; vertical or horizontal shaft configuration; and different priming mechanisms, such as conventional flooded-suction, self-priming, and vacuum-priming. Each of these variations enable pumps to meet certain design criteria, including head, capacity, and efficiency requirements. At the same time, the variations ensure maintenance accessibility, eliminate pump clogging, and accommodate piping needs. For example, if there is a need to produce higher discharge heads, the pump may be modified to include several additional impellers. Another example is if the material being pumped contains a large amount of material that could clog the pump; the pump construction may be modified to remove the major portion of the impeller from direct contact with material being pumped.

There are numerous modifications of the centrifugal pump available. The scope of this handbook covers only those that has found wide application in the water and wastewater treatment industries.

Modifications in this section include:

1. Submersible pumps
2. Recessed impeller or vortex
3. Turbine pumps

7.17.1 Submersible Pumps

The submersible pump is, as the name suggests, placed directly in deep-wells and in wet wells. In some cases, only the pump is submerged, while in other cases, the entire pump-motor assembly is placed in the well or wet well. A simplified diagram of a typical submersible pump is shown in Figure 7.53.

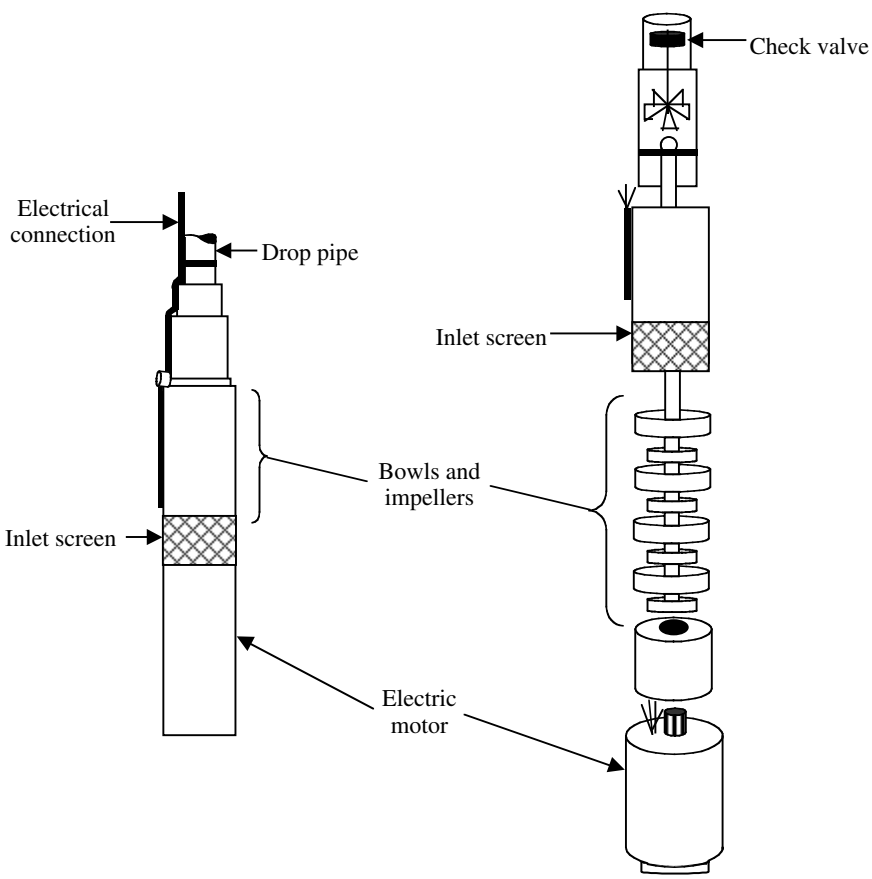

FIGURE 7.53 Submersible pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

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The submersible pump may be either a close-coupled centrifugal pump or an extended shaft centrifugal pump. If the system is a close-coupled pump system, then both motor and pump are submerged in the water or wastewater being pumped. Seals to prevent the water or wastewater from entering the inside of the motor and causing shorts and motor burnout must protect the electric motor in a close-coupled pump.

In the extended shaft system, the pump is submerged while the motor is mounted above the pump well or wet well. In this situation, the pump and motor must be connected by one of the extended shaft assemblies discussed earlier.

7.17.1.1 Applications

The submersible pump has wide applications in the water and/or wastewater treatment industry. It generally can be substituted in any of the applications of other types of centrifugal pumps. However, it has found its widest application in collector system pump stations.

7.17.1.2 Advantages

In addition to the advantages discussed earlier for a conventional centrifugal pump, the submersible pump has other advantages:

1. Because it is located below the surface of the liquid, there is less chance that the pump will lose its prime, develop air leaks on the suction side of the pump, or require initial priming.
2. Because the pump or the entire assembly is located in the well or wet well, there is less cost associated with the construction and operation of this system. There is no need to construct a dry well or a large structure to hold the pumping equipment and necessary controls.

7.17.1.3 Disadvantages

The major disadvantage associated with the submersible pump is the lack of access to the pump or pump and motor. The performance of any maintenance requires either drainage of the well (not likely) or wet well or extensive lift equipment to remove the equipment from the well (more likely), wet well, or both. This may be a major factor in determining if a pump receives the attention it requires. Also, in most cases, all major maintenance on close-coupled submersible pumps must be performed by outside contractors due to the need to reseal the motor to prevent leakage.

7.17.2 Recessed Impeller or Vortex Pumps

The recessed impeller or vortex pump uses an impeller the casing (see Figure 7.54). The spinning action of the impeller creates a vortex or whirlpool. This whirlpool increases the velocity of the material being pumped. As in other centrifugal pumps, this increased velocity is then converted to increased pressure or head.

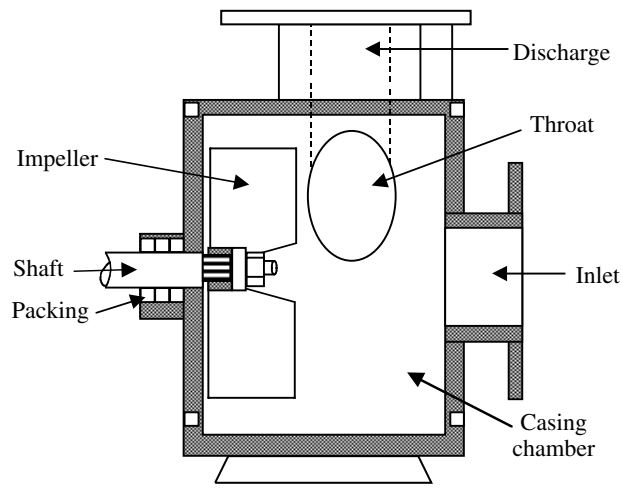

FIGURE 7.54 Schematic of a recessed impeller or vortex pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

7.17.2.1 Applications

The recessed impeller or vortex pump is used widely in applications where the liquid being pumped contains large amounts of solids or debris (e.g., wastewater sludge) that could clog or damage the pump's impeller. It has found increasing use as a sludge pump in facilities that withdraw sludge continuously from their primary clarifiers.

7.17.2.2 Advantages

The major advantage of this modification is the increased ability to handle materials that would normally clog or damage the pump impeller. Because the majority of the flow does not come in direct contact with the impeller, there is much less potential for problems.

7.17.2.3 Disadvantages

Because there is less direct contact between the liquid and the impeller, the energy transfer is less efficient. This results in somewhat higher power costs and limits the pump's application in low to moderate capacities.

Objects that might have clogged a conventional type centrifugal pump are now able to pass through the pump. Although this is very beneficial in reducing pump maintenance requirements, in some situations it can allow material to pass into a less accessible location before

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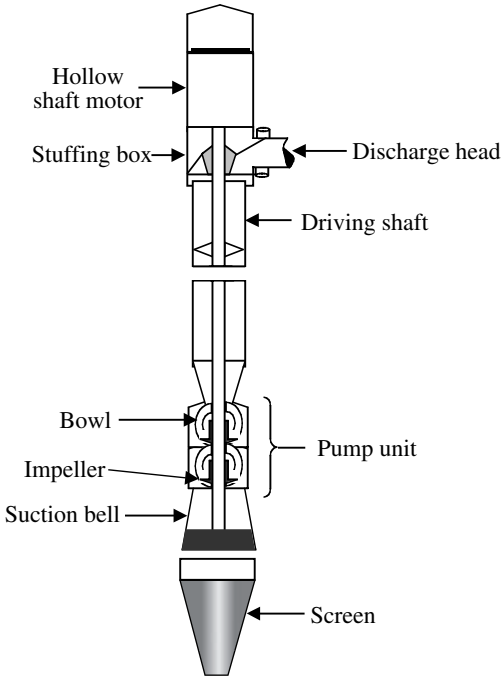

FIGURE 7.55 Vertical turbine pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

becoming an obstruction. To be effective, the piping and valving must be designed to pass objects of a size equal to that which the pump will discharge.

7.17.3 Turbine Pumps

The turbine pump consists of a motor, drive shaft, a discharge pipe of varying lengths, and one or more impeller-bowl assemblies. It is normally a vertical assembly in which the water enters at the bottom, passes axial through the impeller-bowl assembly where the energy transfer occurs, then moves upward through additional impeller-bowl assemblies to the discharge pipe. The length of this discharge pipe will vary with the distance from the wet well to the desired point of discharge (see Figure 7.55). There are two types of turbine pumps: line shaft turbines and can turbines (for dry well installations).

7.17.3.1 Application

Due to the construction of the turbine pump, the major applications have traditionally been for pumping of relatively clean water. The line shaft turbine pump has been used extensively for drinking water pumping, especially where water is withdrawn from deep wells. The main wastewater treatment application has been pumping plant effluent back into the plant for use as service water.

7.17.3.2 Advantages

The turbine pump has a major advantage in the amount of head it is capable of producing. By installing impeller-bowl assemblies, the pressure or head the pump is capable of producing may be increased dramatically.

Note: Adding impeller-bowl assemblies can increase the amount of pressure in a lineshaft turbine pump.

7.17.3.3 Disadvantages

The presence of large amounts of solids within the liquid being pumped can seriously increase the amount of maintenance the pump requires. As a result, in wastewater treatment, the unit has not found widespread use in any situation other than service water pumping.

7.18 POSITIVE-DISPLACEMENT PUMPS

The clearest differentiation between centrifugal (or kinetic) pumps and positive-displacement pumps is made or based on the method by which pumping energy is transmitted to the liquid. As pointed out earlier, centrifugal pumps rely on a transformation of kinetic energy to static pressure. Positive-displacement pumps discharge a given volume for each stroke or revolution (i.e., energy is added intermittently to the fluid flow).

The two most common forms of positive-displacement pumps are reciprocating action pumps (which use pistons, plungers, diaphragms, or bellows) and rotary action pumps (using vanes, screws, lobes, or progressing cavities). All positive-displacement pumps act to force liquid into a system regardless of the resistance that may oppose the transfer. The discharge pressure generated by a positive-displacement pump is, in theory, infinite. If the pump is deadheaded, the pressure generated will increase until either a pump part fails or the driver stalls from lack of power.[32]

Note: Because positive-displacement pumps cannot be operated against a closed discharge valve (i.e., something must be displaced with each stroke of the pump), closing the discharge valve can cause rupturing of the discharge pipe, the pump head, the valve, or some other component.

7.18.1 Reciprocating Pumps

The reciprocating pump (or piston pump) is one type of positive displacement pump. This pump works just like the piston in an automobile engine. On the intake stroke, the intake valve opens, filling the cylinder with liquid. As the piston reverses direction, the intake valve is pushed closed and the discharge valve is pushed open; the liquid is pushed into the discharge pipe. With the next reversal

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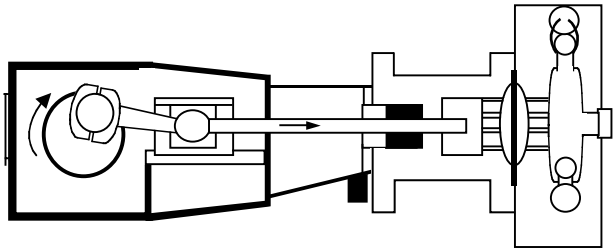

FIGURE 7.56 Diaphragm pump. (From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.)

of the piston, the discharge valve is pulled closed and the intake valve pulled open, and then the cycle repeats.

A piston pump is usually equipped with an electric motor and a gear and cam system that drives a plunger connected to the piston. Just like an automobile engine piston, the piston must have packing rings to prevent leakage. It must also be lubricated to reduce friction. Because the piston is in contact with the liquid being pumped, only good grade lubricants can be used when pumping materials that will be added to drinking water. The valves must be replaced periodically as well.

Four major types of reciprocating pumps exist:

1. Steam pumps
2. Power pumps
3. Diaphragm pumps
4. Metering pumps

In this handbook, because of their application in water and wastewater operations, we discuss the diaphragm and metering pumps only.

7.18.1.1 Diaphragm Pumps

A diaphragm pump is composed of the following

1. A chamber used to pump the fluid
2. A diaphragm that is operated by either electric or mechanical means
3. Two valves assemblies — a suction and a discharge valve assembly (see Figure 7.56)

A diaphragm pump is a variation of the piston pump in which the plunger is isolated from the liquid being pumped by a rubber or synthetic diaphragm. As the diaphragm is moved back-and-forth by the plunger, liquid is pulled into and pushed out of the pump. This arrangement provides better protection against leakage of the liquid being pumped and allows the use of lubricants that otherwise would not be permitted. Care must be taken to assure that diaphragms are replaced before they rupture. Diaphragm pumps are appropriate for discharge pressures up to about 125 psi, but do not work well if they must lift liquids more than about 4 ft.

Diaphragm pumps are frequently used for chemical feed pumps. They are well suited for this purpose because the liquid (corrosive liquids, slurries, abrasive liquids, food, or chemicals) only touches the diaphragm, the suction, and the discharge. By adjusting the frequency of the plunger motion and the length of the stroke, extremely accurate flow rates can be metered. The pump may be driven hydraulically by an electric motor or an electronic driver in which the plunger is operated by a solenoid. Electronically driven metering pumps are extremely reliable (few moving parts) and inexpensive.

7.18.1.2 Metering Pumps

To gain an understanding of what a metering pump is, what it is all about, what it does, what it is capable of doing, we must first contemplate the first, the very first metering pump.

Consider these important points:

1. It is sized to fit the system conditions.
2. It has positive-displacement ability for repeatability, reproducibility, and linearity.
3. The flow rate is adjustable for varying conditions.
4. It is adjustable for varying pressures.
5. It has pulsing or reciprocating action.
6. It has check valves.
7. It is leak proof.
8. It has built-in safety features.
9. It is relatively simple in construction compared to other parts of the system.
10. It is rugged in construction, requiring little maintenance.
11. It can meter two different liquids at the same time and maintain synchronization.
12. All parts of the system depend on it.
13. Although not necessary for a metering pump, it is electrically actuated. The vast majority of metering pumps is capable of other types of actuation.[33]

Fortunately, people were not required to invent the device described above; instead, they were born with it beating inside their chests — the human heart. This very first metering pump, in regards to its simplicity, complexity, design, and efficiency, is without comparison. But we try, as humans, to duplicate what we know works and works so well. In this instance, we know that the human heart is the absolute embodiment of what a metering pump should be. In our quest to design and build the most efficient and practical metering pump we possibly can, we fashion a likeness of and a close resemblance and correlation to the operation of the ultimate model, the human heart. However, we still struggle to build a machine that matches the human heart's metering function.

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We leave our brief review of anatomy and move on to the less dramatic (but just as relevant) world of man-made metering pumps. More specifically, let's move our focus to metering pumps that are commonly used in water and wastewater treatment operations.

Metering pumps have found a wide range of uses in water and wastewater treatment operations. In fact, their use is without comparison with other industries. Simply, the largest area of application of metering pumps is in water and wastewater treatment.

Continuous accurate treatment of water and wastewater is required in all phases of its use, reuse, or disposal. Most raw water supplies and wastewater treatment operations are treated with chlorine to control bacteria growth. Some waterworks meter hydrofluosilicic acid to fluoridate the water for improving growth of teeth in children. Metering pumps are used to add sodium hypochlorite to large private and municipal swimming pools to maintain chlorine levels. Many water sources are lakes and rivers that require addition of such chemicals as algicides to control growth of algae plus other chemicals for cleaning the water and controlling acidity levels. In wastewater treatment the wastestream is cleaned and conditioned before the water is reintroduced into the environment. In this process, lime slurry is metered to control acidity level and polymers, coagulant aids, and ferric chloride for cleaning and conditioning.

Metering pumps are precision instruments and are used to accurately feed a predetermined volume of liquid into a process or system. They also function to pump, or convey, a liquid from one point to another. Although they are positive-displacement type pumps, they do contain special adaptations that are designed primarily to transfer liquid at an accurately controlled rate.

Metering pumps fall into four basic types. They are defined by the method used to seal the liquid end of the pump from the power end, preventing leakage and pumping inaccuracies.

1. Piston packed seal
2. Plunger, gland packed seal
3. Mechanical diaphragm
4. Hydraulic diaphragm seal

The power end of the metering pump is common to all four types, with various designs used to generate the reciprocating movement required to power the liquid end.[34]

Because of our constant demand for new and improved products and our constantly expanding knowledge in chemistry and water and wastewater treatment, there is an ever-increasing demand for precision metering of fluids. Metering pumps provide the precision metering that is needed. Will we ever develop a metering pump to match the capabilities of that human metering pump we all depend on? Do not hold your breath waiting; the jury is still out on that one.

TABLE 7.8
Classes of Rotary Pumps

Rotor Type	Pump Type
Single Rotor	Vane
	Piston
	Flexible member
	Screw
	Progressive cavity
Multiple Rotor	Gear
	Lobe
	Circumferential piston
	Screw

Source: From Spellman, F.R. and Drinan, J., *Pumping,* Technomic Publ., Lancaster, PA, 2001.

7.18.1.3 Rotary Pumps

Positive-displacement rotary pumps provide pumping action by the relative movement between rotating elements of the pump and stationary elements of the pump. Their rotary motion distinguishes them from reciprocating positive-displacement pumps since the main motion of moving elements is reciprocating.[35] Rotary pumps are primarily used as a source of fluid power in hydraulic systems. A few types are in common use in waterworks operations.

Rotary pumps constitute a large class and are used for relatively low flow and moderate pressures. Certain configurations, especially when used in hydraulic systems, may develop several thousand pounds per square inch. Table 7.8 lists the many configurations possible.

While any of the rotary pump types listed in Table 7.8 may find applications in water and wastewater treatment, in this handbook we focus on the progressive-cavity pump, because of its ability to handle a wide range of fluids, from clear water to viscous solutions such as thick sludge slurries.

7.18.1.4 Progressive-Cavity Pump

The progressive-cavity pump is composed of five main parts: the housing, the stator, the rotor, the connecting rod, and the drive shaft. The rotor is usually made of either chrome-plated tool steel or stainless steel. The stator is made from natural rubber or other materials. The material selected for the rotor and stator is determined by the application. The progressive-cavity pump can achieve up to 2,000 psi, depending on pump length.

In operation, liquid travels in the spaces between the rotor and the flexible stator. The rotor revolves rapidly, and capacity is directly proportional to rotor speed and pump size, producing a nonpulsing flow. No valves are associated with the pumping, but packing is needed to prevent liquid from leaking out of the pump and up the

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shaft. Rotor and stator are always in contact (the liquid lubricates them) as they move.[36]

Note: A progressive-cavity pump should never be allowed to run dry, because it will quickly burn up and the stator will fail.

7.18.1.5 Special Purpose Pumps

There are several special purpose positive-displacement pumps. The pump we concentrate on in this handbook is the peristaltic pump.

7.18.1.5.1 Peristaltic Pumps

Peristaltic pumps (sometimes called tubing pumps) use a series of rollers to compress plastic tubing to move the liquid through the tubing. A rotary gear turns the rollers at a constant speed to meter the flow. Peristaltic pumps are mainly used as chemical feed pumps.

The flow rate is adjusted by changing the speed the roller-gear rotates (to push the waves faster) or by changing the size of the tubing (so there is more liquid in each wave). As long as the right type of tubing is used, peristaltic pumps can operate at discharge pressures up to 100 psi. Note that the tubing must be resistant to deterioration from the chemical being pumped. The principle item of maintenance is the periodic replacement of the tubing in the pump head. There are no check valves or diaphragms in this type of pump.

7.19 CHAPTER REVIEW QUESTIONS AND PROBLEMS

7.1. Applications in which chemicals must be metered under high pressure require high-powered _____ pumps.

7.2. _____ materials are materials that resist any flow-producing force.

7.3. What type of pump is usually used for pumping high-viscosity materials?

7.4. High-powered positive-displacement pumps are used to pump chemicals that are under _____ pressure.

7.5. _____ viscosity materials are thick.

7.6. When the _____ of a pump impeller is above the level of the pumped fluid, the condition is called suction lift.

7.7. When a pump is not running, conditions are referred to as _____; when a pump is running, the conditions are _____.

7.8. With the pump _____, the difference in elevation between the suction and discharge liquid levels is called static head.

7.9. Velocity head is expressed mathematically as _____.

7.10. The sum of total static head, head loss, and dynamic head is called _____.

7.11. What are the three basic types of curves used for centrifugal pumps?

7.12. The liquid used to rate pump capacity is _____.

7.13. Because of the reduced amount of air pressure at high altitudes, less _____ is available for the pump.

7.14. With the pump shut off, the difference between the suction and discharge liquid levels is called _____.

7.15. _____ and _____ is the largest single contributing factor to the reduction of pressure at a pump impeller.

7.16. The operation of a centrifugal pump is based on _____.

7.17. The casing of a pump encloses the pump impeller, the shaft, and the _____.

7.18. The _____ is the part of the pump that supplies energy to the fluid.

7.19. If wearing rings are used only on the volute case, we must replace the _____ and _____ at the same time.

7.20. Which part of the end-suction pump directs water flow into and out of the pump?

7.21. What is the function of the pump's impeller?

7.22. The _____ pump has no bearings.

7.23. _____ split casings split perpendicular to the pump shaft.

7.24. Name three types of impellers.

7.25. A _____ casing adds a guiding vane to the fluid passage.

7.26. The impeller does not _____ the water it is pumping, but _____ through the water and throws it.

7.27. A physical separation between the high and low-pressure sides of a pump is maintained by _____.

7.28. Identify the components indicated in the drawing below. Compare the numbers on the drawing to the list provided.

____ a. Volute case	____ f. Thrust bearing
____ b. Packing gland	____ g. Suction
____ c. Impeller	____ h. Discharge
____ d. Stuffing box	____ i. Radial bearing
____ e. Slinger ring	____ j. Impeller wears ring

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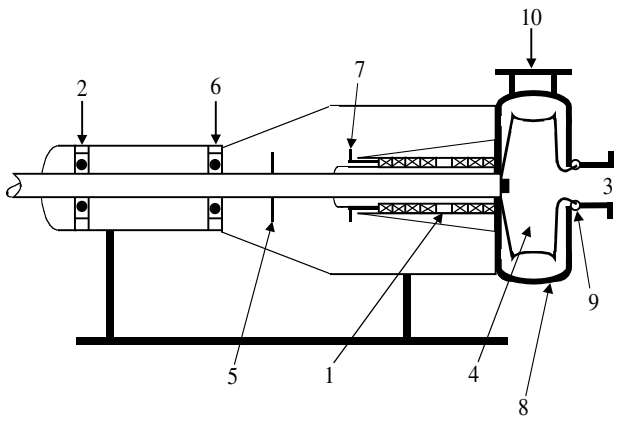

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8 Water and Wastewater Conveyance

The design considerations for the piping system are the function of the specifics of the system. However, all piping systems have a few common issues: the pipe strength must be able to resist internal pressure, handling, and earth and traffic loads; the pipe characteristics must enable the pipe to withstand corrosion and abrasion and expansion and contraction of the pipeline (if the line is exposed to atmospheric conditions); engineers must select the appropriate pipe support, bedding, and backfill conditions; the design must account for the potential for pipe failure at the connection point to the basins due to subsidence of a massive structure; and the composition of the pipe must not give rise to any adverse effects on the health of consumers.[1]

8.1 DELIVERING THE LIFEBLOOD OF CIVILIZATION

Conveyance or piping systems resemble veins, arteries and capillaries. According to Nayyar, "they carry the lifeblood of modern civilization. In a modern city they transport water from the sources of water supply to the points of distribution; convey waste from residential and commercial buildings and other civic facilities to the treatment facility or the point of discharge."[2]

Water and wastewater operators must be familiar with piping, piping systems, and the many components that make piping systems function. Operators are directly concerned with various forms of piping, tubing, hose, and the fittings that connect these components to create workable systems.

This chapter covers important, practical information about the piping systems that are a vital part of plant operation, essential to the success of the total activity. To prevent major system trouble, skilled operators are called upon to perform the important function of preventive maintenance to avoid major breakdowns, and must be able to make needed repairs when breakdowns do occur. A comprehensive knowledge of piping systems and accoutrements is essential to maintaining plant operations.

8.2 CONVEYANCE SYSTEMS

In regard to early conveyance systems, the prevailing practice in medieval England was the use of closed pipes. This practice was contrary to the Romans who generally employed open channels in their long-distance aqueducts and used pipes mainly to distribute water within cities. The English preferred to lay long runs of pipes from the water source to the final destination. The Italians, on the other hand, where antique aqueduct arches were still visible, seem to have had more of a tendency to follow the Roman tradition of long-distance channel conduits. At least some of the channel aqueducts seem to have fed local distribution systems of lead or earthenware pipes.[3]

With today's water and wastewater conveyance, not much has changed from the past. Our goal today remains the same: (1) convey water from source to treatment facility to user, and (2) convey wastewater from user to treatment to the environment.

In water and wastewater operations, the term conveyance or piping system refers to a complete network of pipes, valves, and other components. For water and wastewater operations in particular, the piping system is all-inclusive; it includes both the network of pipes, valves, and other components that bring the flow (water or wastewater) to the treatment facility, as well as piping, valves and other components that distribute treated water to the end user and treated wastewater to outfall. In short, all piping systems are designed to perform a specific function.

Probably the best way to illustrate the importance of a piping system is to describe many of its applications used in water and wastewater operations. In the modern water and wastewater treatment plant piping systems are critical to successful operation. In water/wastewater operations, fluids and gases are used extensively in processing operations; they usually are conveyed through pipes. Piping carries water and wastewater into the plant for treatment, fuel oil to heating units, steam to steam services, lubricants to machinery, compressed air to pneumatic service outlets for air-powered tools, etc., and chemicals to unit processes. In water treatment alone, Kawamura points out that there are "six basic piping systems: (1) raw water and finished waste distribution mains; (2) plant yard piping that connects the unit processes; (3) plant utility, including the fire hydrant lines; (4) chemical lines; (5) sewer lines; and (6) miscellaneous piping, such as drainage and irrigation lines."[4]

Besides raw water, treated water, wastewater influent, and treated wastewater effluent, the materials conveyed through piping systems include oils, chemicals, liquefied gases, acids, paints, sludge, and many others.

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Important Point: Because of the wide variety of materials that piping systems can convey, the components of piping systems are made of different materials and are furnished in many sizes to accommodate the requirements of numerous applications. For example, pipes and fittings can be made of stainless steel, many different types of plastic, brass, lead, glass, steel, and cast iron.

Any waterworks or wastewater treatment plant has many piping systems, not just the systems that convey water and wastewater. Along with those mentioned earlier, keep in mind that plant-piping systems also include those that provide hot and cold water for plant personnel use. Another system heats the plant, while another may be used for air conditioning.

Water and wastewater operators have many responsibilities and basic skills. The typical plant operator is skilled in heating, ventilation, and air conditioning systems; chemical feed systems, and mechanical equipment operation and repair in piping system maintenance activities. However, only the fluid transfer systems are important to us in this text. The units that the piping system serves or supplies (such as pumping, unit processes, and machines) are discussed in other chapters of the text.

For water and wastewater operators, a familiar example of a piping system is the network of sodium hypochlorite pipes in treatment plants that use this chemical for disinfection and other purposes. The whole group of components — pipes, fittings, and valves — working together for one purpose makes up a *system*. This particular system has a definite purpose — to carry sodium hypochlorite and distribute it, conveying it to point of application.

Note: This chapter is concerned only with the piping system used to circulate the chemical, not with the hypochlorination equipment itself. Our concern begins where the chemical outlet is connected to the storage tank and continues to the point where the pipe is connected to the point of application. The piping, fittings, and valves of the hypochlorination pipeline (and others) are important to us. Gate, needle, pressure-relief, air-and-vacuum relief, diaphragm, pinch butterfly, check, rotary and globe valves, traps, expansion joints, plugs, elbows, tee fittings, couplings, reducers, laterals, caps, and other fittings help ensure the effective flow of fluids through the lines. As you trace a piping system through your plant site, you will find many of them (see Figure 8.1). They are important because they are directly related to the operation of the system. Piping system maintenance is concerned with keeping the system functioning properly, and to function properly, piping systems must be kept closed and leak proof.

Important Point: Figure 8.1 shows a single-line diagram that is similar to an electrical schematic. It uses symbols for all the diagram components. A double-line diagram (not shown here) is a pictorial view of the pipe, joints, valves and other major components similar to an electrical wiring diagram, instead of an electrical schematic.

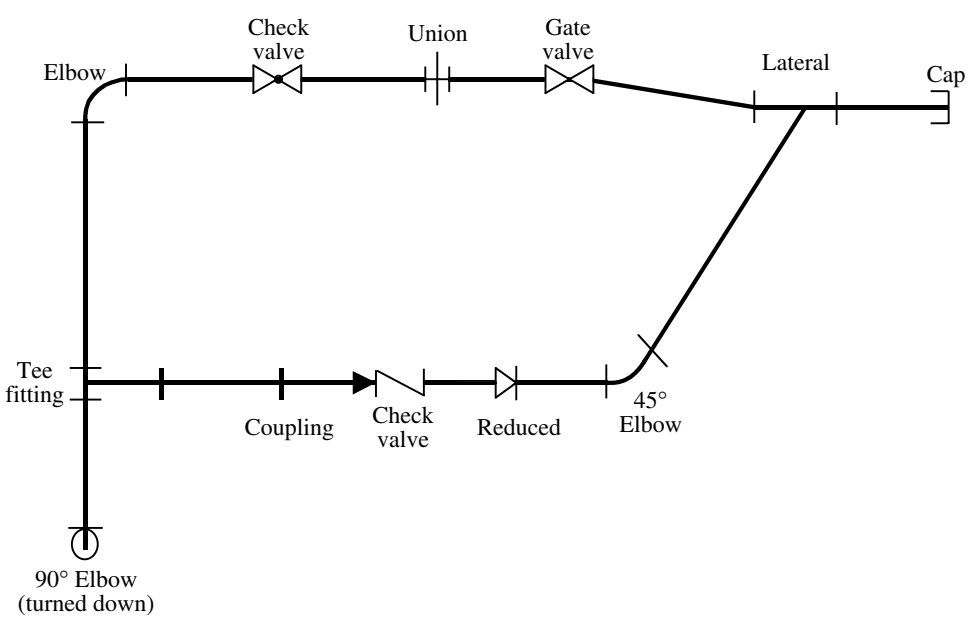

FIGURE 8.1 Shows various components in a single-line piping diagram. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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8.2.1 Definitions

Key terms related to water and wastewater conveyance are listed and defined in this section.

Absolute pressure gauge pressure plus atmospheric pressure.

Alloy a substance composed of two or more metals.

Anneal to heat and then cool a metal in order to make it softer and less brittle.

Annealing process of heating and then cooling a metal, usually to make it softer and less brittle.

Asbestos fibrous mineral form of magnesium silicate.

Backsiphonage a condition in which the pressure in the distribution system is less than atmospheric pressure, which allows contamination to enter a water system through a cross-connection.

Bellows a device that uses a bellows for measuring pressure.

Bimetallic made of two different types of metal.

Bourbon tube a semicircular tube of elliptical cross section, used to sense pressure changes.

Brazing soldering with a nonferrous alloy that melts at a lower temperature than that of the metals being joined; also known as hard soldering.

Butterfly valve a valve in which a disk rotates on a shaft as the valve opens and closes. In the full open position, the disk is parallel to the axis of the pipe.

Carcass the reinforcement layers of a hose, between the inner tube and the outer cover.

Cast iron a generic term for the family of high carbon-silicon-iron casting alloys including gray, white, malleable, and ductile iron.

Check valve a valve designed to open in the direction of normal flow and close with reversal of flow. An approved check valve has substantial construction and suitable materials, is positive in closing, and permits no leakage in a direction opposite to normal flow.

Condensate steam that condenses into water in a piping system.

Diaphragm valve a valve in which the closing element is a thin, flexible disk often used in low-pressure systems.

Differential pressure the difference between the inlet and outlet pressures in a piping system.

Double-line diagram pictorial view of the pipes, joints, valves, and other major components similar to an electrical wiring diagram.

Ductile a term applied to a metal that can be fashioned into a new form without breaking.

Expansion joint absorbs thermal expansion or contraction in piping systems.

Extruding process of shaping a metal or plastic by forcing it through a die.

Ferrous a term applied to a metal that contains iron.

Ferrule a short bushing used for making a tight connection.

Filter an accessory fitting used to remove solids from a fluid stream.

Fluids any substance that flows.

Flux used in soldering to prevent the formation of oxides during the soldering operation and to increase the wetting action so solder can flow more freely.

Friable readily crumbled by hand.

Gate valve a valve in which the closing element consists of a disk that slides across an opening to stop the flow of water.

Gauge pressure the amount by which the total absolute pressure exceeds the ambient atmospheric pressure.

Globe valve a valve having a round, ball-like shell and horizontal disk.

Joint a connection between two lengths of pipe or between a length of pipe and a fitting.

Laminar flow arranged in or consisting of thin layers.

Mandrel a central core or spindle around which material may be shaped.

Neoprene a synthetic material that is highly resistant to oil, flame, various chemicals, and weathering.

Metallurgy the science and study of metals.

Nominal pipe size the thickness given in the product material specifications or standard to which manufacturing tolerances are applied.

Nonferrous a term applied to a material that does not contain iron.

Piping systems a complete network of pipes, valves, and other components.

Ply one of several thin sheets or layers of material.

Prestressed concrete concrete that has been compressed with wires or rods in order to reduce or eliminate cracking and tensile forces.

Pressure-regulating valve a valve with a horizontal disk for automatically reducing water pressures in a main to a preset value.

PVC polyvinyl chloride plastic pipe.

Schedule approximate value of the expression 1000 P/S, where P is the service pressure and S is the allowable stress, both expressed in pounds per square inch.

Single-line diagram uses symbols for all the diagram components.

Soldering a form of brazing in which nonferrous filler metals having melting temperatures below 800ºF (427ºC) are used. The filler material is called solder and is distributed between surfaces by capillary action.

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Solenoid an electrically energized coil of wire surrounding a movable iron case.

Stainless steel an alloy steel having unusual corrosion-resisting properties, usually imparted by nickel and chromium.

Strainer an accessory fitting used to remove large particles of foreign matter from a fluid.

Throttle controlling flow through a valve by means of intermediate steps between fully open and fully closed.

Tinning covering metal to be soldered with a thin coat of solder to work properly. Overheating or failure to keep the metal clean causes the point to become covered with oxide. The process of replacing this coat of oxide is called tinning.

Trap an accessory fitting used to remove condensate from steam lines.

Vacuum breaker a mechanical device that allows air into the piping system thereby preventing backflow that could otherwise be caused by the siphoning action created by a partial vacuum.

Viscosity the thickness or resistance to flow of a liquid.

Vitrified clay clay that has been treated in a kiln to produce a glazed, watertight surface.

Water hammer the concussion of moving water against the sides of pipe, caused by a sudden change in the rate of flow or stoppage of flow in the line.

8.2.2 Fluids vs. Liquids

We use the term fluids throughout this text to describe substances being conveyed through various piping systems from one part of the plant to another. We normally think of pipes conveying some type of liquid substance, which most of us take to have the same meaning as fluid, but there is a subtle difference between the two terms. The dictionary's definition of fluid is any substance that flows — which can mean a liquid or gas (air, oxygen, nitrogen, etc.). Some fluids carried by piping systems include thick viscous mixtures, such as sludge, in a semi-fluid state. Although sludge and other such materials might seem more solid (at times) than liquid, they do flow, and are considered fluids.

In addition to carrying liquids such as oil, hydraulic fluids, and chemicals, piping systems carry compressed air and steam, which also are considered fluids because they flow.

Important Point: Fluids travel through a piping system at various pressures, temperature, and speeds.

8.2.3 Maintaining Fluid Flow in Piping Systems

The primary purpose of any piping system is to maintain free and smooth flow of fluids through the system. Another purpose is to ensure that the fluids being conveyed are kept in good condition (i.e., free of contamination).

Piping systems are purposely designed to ensure free and smooth flow of fluids throughout the system, but additional system components are often included to ensure that fluid quality is maintained. Piping system filters are one example, and strainers and traps are two others.

It is extremely important to maintain free and smooth flow and fluid quality in piping systems, especially those that feed vital pieces of equipment and machinery. Consider the internal combustion engine, for example. Impurities such as dirt and metal particles can damage internal components and cause excessive wear and eventual breakdown. To help prevent such wear, the oil is run continuously through a filter designed to trap and filter out the impurities.

Other piping systems need the same type of protection that the internal combustion engine does, which is why most piping systems include filters, strainers, and traps. These filtering components may prevent damage to valves, fittings, the pipe, and to downstream equipment/machinery. Chemicals, various types of waste products, paint, and pressurized steam are good examples of potentially damaging fluids. Filters and strainers play an important role in piping systems, protecting both the piping system and the equipment that the piping system serves.

8.2.3.1 Scaling

Because sodium and calcium hypochlorite are widely used in water and wastewater treatment operations, problems common in piping systems feeding this chemical are of special concern. In this section, we discuss *scaling* problems that can occur in piping systems that convey hypochlorite solution.

To maintain the chlorine in solution (used primarily as a disinfectant), sodium hydroxide (caustic) is used to raise the pH of the hypochlorite; the excess caustic raises the shelf life. A high pH caustic solution raises the pH of the dilution water to over pH 9.0 after it is diluted. The calcium in the dilution water reacts with dissolved CO_2 and forms calcium carbonate. Experience has shown that 2-in. pipes have turned into 3/4-in. pipes due to scale buildup. The scale deposition is greatest in areas of turbulence such as pumps, valves, rotameters, backpressure devices, etc.

If lime (calcium oxide) is added (for alkalinity), plant water used as dilution water will have higher calcium levels and generates more scale. While it is true that softened water will not generate scale, it is also true that it is expensive in large quantities. Many facilities use softened water on hypochlorite mist odor scrubbers only.

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Scaling also often occurs in solution rotameters, making flow readings impossible and freezing the flow indicator in place. Various valves can freeze up and pressure-sustaining valves freeze and become plugged. Various small diffuser holes fill with scale. To slow the rate of scaling, many facilities purchase water from local suppliers to dilute hypochlorite for the return activated sludge (RAS) and miscellaneous uses.

Some facilities have experimented with the system by not adding lime to it. When they did this, manganese dioxide (black deposits) developed on the rotameter's glass, making viewing the float impossible. In many instances, moving the point of hypochlorite addition to downstream of the rotameter seemed to solve the problem.

If remedial steps are not taken, scaling from hypochlorite solutions can cause problems. For example, scale buildup can reduce the inside diameter of pipe so much that the actual supply of hypochlorite solution required to properly disinfect water or wastewater was reduced. As a result, the water sent to the customer or outfalled to the receiving body may not be properly disinfected. Because of the scale buildup, the treatment system itself will not function as designed and could result in a hazardous situation in which the reduced pipe size increases the pressure level to the point of catastrophic failure. Scaling, corrosion, or other clogging problems in certain piping systems, are far from an ideal situation.

EXAMPLE 8.1

For explanation purposes, the scale problem is taken a step further by use of example. Assume that we have a piping system designed to provide chemical feed to a critical plant unit process. If the motive force for the chemical being conveyed is provided by a positive-displacement pump at a given volume of solution at 70 psi through clean pipe. After clogging takes place, the pump continues trying to force the same volume of chemical through the system at 70 psi, but the pressure drops to 25 psi. Friction caused the pressure drop. The reduction of the inside diameter of the pipe increased the friction between the chemical solution and the inside wall of the pipe.

Important Point: A basic principle in fluid mechanics states that fluid flowing through a pipe is affected by friction — the greater the friction, the greater the loss of pressure.

Important Point: Another principle or rule states that the amount of friction increases as the square of the velocity. (**Note:** speed and velocity are not the same, but common practice refers to the velocity of a fluid.) In short, if the velocity of the fluid doubles, the friction is quadrupled compared to what it was before. If the velocity is multiplied by 5, the friction is multiplied by 25, and so on.

In Example 8.1, the pressure dropped from 70 to 25 psi because the solution had to run faster to move through the pipe. Because the velocity of the solution pushed by the pump had to increase to levels above what it was when the pipe was clean, the friction increased at a higher rate than before. The fiction loss was the reason that a pressure of 25 psi reached the far end of the piping system. The equipment designed to operate at a pressure of 70 psi could not work on the 25 psi of pressure being supplied.

Important Point: After reviewing the previous example, you might ask: Why couldn't the pump be slowed down so that the chemical solution could pass more slowly through the system, thus avoiding the effect of increased friction? Lower pressure results as pump speed is reduced. This causes other problems as well. Pumps that run at a speed other than that for which they are designed do so with a reduction in efficiency.

What is the solution to our pressure loss problem in Example 8.1? Actually, we can solve this problem two possible ways: either replace the piping or clean it.

Replacing the piping or cleaning it sounds simple and straightforward, but it can be complicated. If referring to a pipe that is relatively short, no more than 20 to a few hundred feet in length, then we may decide to replace the pipe. What would we do if the pipe were 3 to 5 mi or more in length? Cleaning this length of pipe probably makes more sense than replacing its entire length. Each situation is different, requiring remedial choices based on practicality and expense.

8.2.4 PIPING SYSTEM MAINTENANCE

Maintaining a piping system can be an involved process. Good maintenance practices can extend the life of piping system components and rehabilitation can further prolong their life.

The performance of a piping system depends on the ability of the pipe to resist unfavorable conditions and to operate at or near the capacity and efficiency that it was designed for. This performance can be checked in several ways: flow measurement, fire flow tests, loss-of-head tests, pressure tests, simultaneous flow and pressure tests, tests for leakage, and chemical and bacteriological water tests. These tests are an important part of system maintenance. They should be scheduled as part of the regular operation of the system.[5]

Most piping systems are designed with various protective features, including minimizing wear and catastrophic failure, and therefore the amount of maintenance

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required. Such protective features include pressure relief valves, blow-off valves, and clean-out plugs.

1. Pressure relief valves — A valve that opens automatically when the fluid pressure reaches a preset limit to relieve the stress on a piping system.
2. Blow-off valve — A valve that can be opened to blow out any foreign material in a pipe.
3. Clean-out plug — A threaded plug that can be removed to allow access to the inside of the pipe for cleaning.

Important Point: Use caution when removing a clean-out plug from a piping system. Before removing the plug, pressure must be cut off and the system bled of residual pressure.

Many piping systems (including water distribution networks and wastewater lines and interceptors) can be cleaned either by running chemical solvents through the lines or by using mechanical clean-out devices.

8.2.5 Valves

Depending on the complexity of the piping system, the number of valves included in a system can range from no more than one in a small, simple system to a large number in very complex systems such as water distributions systems. Valves are necessary for both the operation of a piping system and for control of the system and system components. In water and wastewater treatment, this control function is used to control various unit processes, pumps, and other equipment.

Valves also function as protective devices. For example, valves used to protect a piping system may be designed to open automatically to vent fluid out of the pipe when the pressure in the lines becomes too high. In lines that carry liquids, relief valves preset to open at a given pressure are commonly used.

Important Point: Not all valves function as safety valves. For example, hand-operated gate and globe valves function primarily as control valves.

The correct size and type of valve is selected for each use. Most valves require periodic inspection to ensure they are operating properly.

8.2.6 Piping System Accessories

Along with valves, piping systems typically include accessories such as pressure and temperature gauges, filters, strainers, and pipe hangers and supports.

1. Pressure gauges — These gauges show what the pressure in the piping system is.
2. Temperature gauges — These gauges show what the temperature in the piping system is.
3. Filters and strainers — These accessories are installed in piping systems to help keep fluids clean and free from impurities.
4. Pipe hangers and supports — These accessories support piping to keep the lines straight and prevent sagging, especially in long runs. Various types of pipe hangers and supports are shown in Figure 8.2.

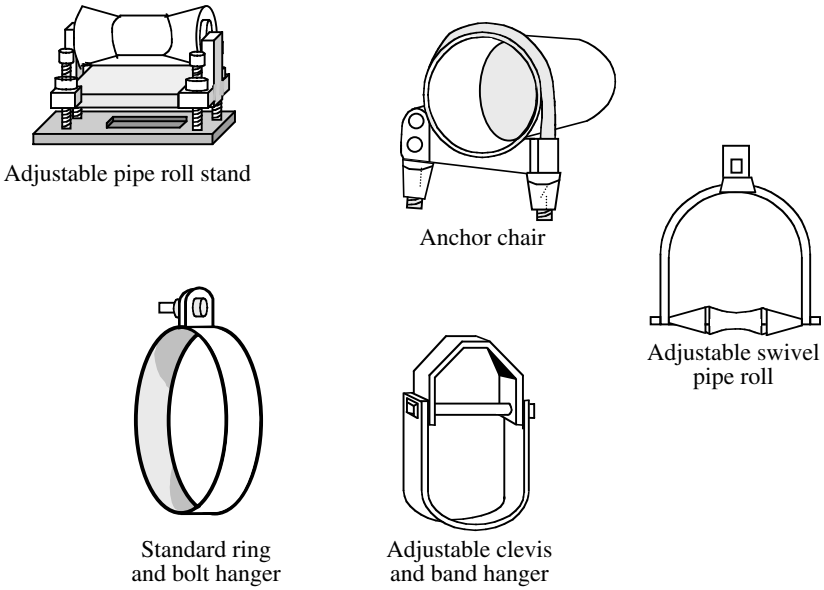

FIGURE 8.2 Pipe hangers and supports. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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8.2.7 Piping Systems: Temperature Effects

Most materials, especially metals, expand as the temperature increases and contract as the temperature decreases. This can be a significant problem in piping systems. To combat this problem, and to allow for expansion and contraction in piping systems, expansion joints must be installed in the line between sections of rigid pipe. An expansion joint absorbs thermal expansion and terminal movement; as the pipe sections expand or contract with the temperature, the expansion joint expands or compresses accordingly, eliminating stress on the pipes.

8.2.8 Piping Systems: Insulation

You do not need to wander too far in most plant sites to find pipes covered with layers of piping insulation. Piping insulation amounts to wrapping the pipe in an envelopment of insulating material. The thickness of the insulation depends on the application. Under normal circumstances, heat passes from a hot or warm surface to a cold or cooler one. Insulation helps prevent hot fluid from cooling as it passes through the system. For systems conveying cold fluid, insulation helps keep the fluid cold.

Materials used for insulation vary, and they are selected according to the requirements of application. Various types of insulating materials are also used to protect underground piping against rusting and corrosion caused by exposure to water and chemicals in the soil.

8.3 METALLIC PIPING

Pipe materials that are used to transport water may also be used to collect wastewater. It is more usual, however, to employ less expensive materials since wastewater lines rarely are required to withstand any internal pressure. Iron and steel pipe are used to convey wastewater only under unusual loading conditions or for force mains (interceptor lines) in which the wastewater flow is pressurized.[6]

8.3.1 Piping Materials

Materials selected for piping applications must be chosen with the physical characteristics needed for the intended service in mind. For example, the piping material selected must be suitable for the flow medium and the given operating conditions of temperature and pressure during the intended design life of the product. For long-term service capability, the material's mechanical strength must be appropriate; the piping material must be able to resist operational variables such as thermal or mechanical cycling. Extremes in application temperature must also be considered in respect to material capabilities.

Environmental factors must also be considered. The operating environment surrounding the pipe or piping components affects pipe durability and life span. Corrosion, erosion, or a combination of the two can result in degradation of material properties or loss of effective load-carrying cross section. The nature of the substance contained by the piping is also an important factor.

Knowledge of the basic characteristics of the metals and nonmetals used for piping provides clues to the uses of the piping materials with which we work in water and wastewater treatment operations. Such knowledge is especially helpful to operators, making their job much easier and more interesting. In this section, metallic piping is discussed. Piping joints, how to join or connect sections of metallic piping, and how to maintain metallic pipe are also discussed.

8.3.2 Piping: The Basics

Earlier, we pointed out that piping includes pipes, flanges, fittings, bolting, gaskets, valves, and the pressure-containing portions of other piping components.

Important Point: According to Nayyar, "a *pipe* is a tube with round cross section conforming to the dimensional requirements of ASME B36.10M (Welded and Seamless Wrought Steel Pipe) and ASME B36.19M (Stainless Steel Pipe)."[7]

Piping also includes pipe hangers and supports and other accessories necessary to prevent overpressurization and overstressing of the pressure-containing components. From a system viewpoint, a pipe is one element or a part of piping. Accordingly, when joined with fittings, valves, and other mechanical devices or equipment, pipe sections are called *piping*.

8.3.2.1 Pipe Sizes

With time and technological advancements (development of stronger and corrosion-resistant piping materials), pipe sizes have become standardized and are usually expressed in inches or fractions of inches. As a rule, the size of a pipe is given in terms of its outside or inside diameter. Figure 8.3 shows the terminology that applies to a section of pipe. Pipes are designated by diameter. The principal dimensions are:

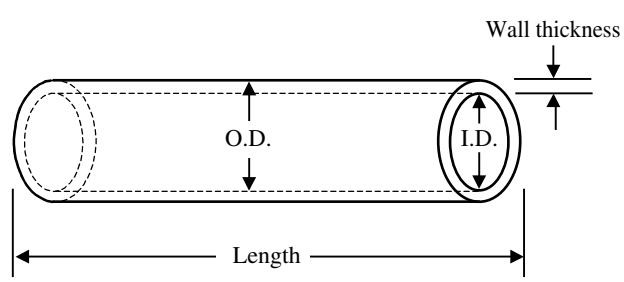

FIGURE 8.3 Pipe terminology. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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1. Wall thickness
2. Length
3. Outside diameter (O.D.) — used to designate pipe greater than 12 in. in diameter
4. Inside diameter (I.D.) — used to designate pipe less than 12 in. in diameter

Important Point: Another important pipe consideration not listed above or shown in Figure 8.3 is weight per foot, which varies according to the pipe material and pipe's wall thickness.

In the continuing effort to standardize pipe size and wall thickness of pipe, the designation nominal pipe size (NPS) replaced the iron pipe size designation; the term schedule (SCH) was developed to specify the nominal wall thickness of pipe.

The NPS diameter (approximate dimensionless designator of pipe size) is generally somewhat different from its actual diameter. For example, the pipe we refer to as a 3-in. diameter pipe has an actual O.D. of 3.5 in., while the actual O.D. of a 12-in. pipe may be .075 in. greater (i.e., 12.750 in.) than the nominal diameter. On the other hand, a pipe 14 in. or greater in diameter has an actual O.D. equal to the nominal size. The inside diameter will depend upon the pipe wall thickness specified by the schedule number.

Important Point: Keep in mind that whether the O.D. is small or large, the dimensions must be within certain tolerances in order to accommodate various fittings.

8.3.2.2 Pipe Wall Thickness

Original pipe wall thickness designations of STD (standard), XS (extra-strong), and XXS (double extra-strong) are still in use today; however, because this system allowed no variation in wall thickness, and because pipe requirements became more numerous, greater variation was needed. As a result, pipe wall thickness, or schedule, today is expressed in numbers (5, 5S, 10, 10S, 20, 20S, 30, 40, 40S, 60, 80, 80S, 100, 120, 140, 160). (Note: You will often hear piping referred to either in terms of its diameter or Schedule number.) The most common schedule numbers are 40, 80, 120, and 160. The outside diameter of each pipe size is standardized. Therefore, a particular nominal pipe size will have a different inside diameter depending upon the schedule number specified. For example, a Schedule 40 pipe with a 3-in. nominal diameter (actual O.D. of 3.500 in.) has a wall thickness of 0.216 in. The same pipe in a Schedule 80 (XS) would have a wall thickness of 0.300 in.

Important Point: A schedule number indicates the approximate value of the expression 1000 P/S, where P is the service pressure and S is the allowable stress, both expressed in pounds per square inch (psi). The higher the schedule number, the thicker the pipe is.

Important Point: The schedule numbers followed by the letter S are per ASME B36.19M, and they are primarily intended for use with stainless steel pipe.[8]

8.3.2.3 Piping Classification

The usual practice is to classify pipe in accordance with the pressure-temperature rating system used for classifying flanges. However, because of the increasing variety and complexity of requirements for piping, a number of engineering societies and standards groups have devised codes, standards, and specifications that meet most applications. By consulting such codes, (e.g., American Society for Testing and Materials [ASTM], Manufacturer's Specifications, National Fire Protection Association [NFPA], American Water Works Association [AWWA], and others), a designer can determine exactly what piping specification should be used for any application.

Important Point: Because pipelines often carry hazardous materials and fluids under high pressures, following a code helps ensure the safety of personnel, equipment, and the piping system.

8.3.2.3.1 ASTM Ratings

ASTM publishes standards (codes) and specifications that are used to determine the minimum pipe size and wall thickness to use in given application.

8.3.2.3.2 Manufacturer's Rating

Pipe manufacturers, because of propriety design of pipe, fitting, or joint, often assign a pressure-temperature rating that may form the design basis or the piping system. (Note: In addition, the manufacturer may impose limitations that must be adhered.)

Important Point: Under no circumstances shall the manufacturer's rating be exceeded.

8.3.2.3.3 NFPA Ratings

Certain piping systems fall within the jurisdiction of NFPA. These pipes are required to be designed and tested to certain required pressures (usually rated for 175 psi, 200 psi, or as specified).

8.3.2.3.4 AWWA Ratings

AWWA publishes standards and specifications that are used to design and install water pipelines and distribution system piping. The ratings used may be in accordance with the flange ratings of AWWA, or the rating could be based upon the rating of the joints used in the piping.

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8.3.2.3.5 Other Ratings

Sometimes a piping system may not fall within the above related rating systems. In this case, the designer may assign a specific rating to the piping system. This is a common practice in classifying or rating piping for main steam or hot reheat piping of power plants, whose design pressure and design temperature may exceed the pressure-temperature rating of ASME B16.5. In assigning a specific rating to such piping, the rating must be equal to or higher than the design conditions.

Important Point: The rating of all pressure-containing components in the piping system must meet or exceed the specific rating assigned by the designer.[9]

When piping systems are subjected to full-vacuum conditions or submerged in water, they experience both the internal pressure of the flow medium and external pressure. In such instances, piping must be rated for both internal and external pressures at the given temperature. Moreover, if a piping system is designed to handle more than one flow medium during its different modes of operation, it must be assigned a dual rating for two different flow media.

8.3.3 Types of Piping Systems

Piping systems consist of two main categories: process lines and service lines. Process lines convey the flow medium used in a manufacturing process or a treatment process (such as fluid flow in water and wastewater treatment). For example, one of the major unit process operations in wastewater treatment is the sludge digestion. The sludge is converted from bulky, odorous, raw sludge to a relatively inert material that can be rapidly dewatered with the absence of obnoxious odors. Because sludge digestion is a unit process operation, the pipes used in the system are called process lines.

Service lines (or utility lines) carry water, steam, compressed air, air conditioning fluids, and gas. Normally, all or part of the plant's general service system is composed of service lines. Service lines cool and heat the plant, provide water where it is needed, and carry the air that drives air equipment and tools.

8.3.3.1 Code for Identification of Pipelines

Under guidelines provided by the American National Standards Institute (ANSI-A 13.1 [current date]), a code has been established for the identification of pipelines. This code involves the use of nameplates (tags), legends, and colors. The code states that the contents of a piping system shall be identified by lettered legend giving the name of the contents. In addition, the code requires that information relating to temperature and pressure should be included. Stencils, tape, or markers can be used to accomplish the marking. To identify the characteristic hazards of the contents, color should be used, but its use must be in combination with legends.

Important Point: Not all plants follow the same code recommendations, which can be confusing if you are not familiar with the system used. Standard piping color codes are often used in water and wastewater treatment operations. Plant maintenance operators need to be familiar with the pipe codes used in their plants.

8.3.4 Metallic Piping Materials

In the not too distant past, it was not (relatively speaking) that difficult to design certain pipe delivery systems. For example, several hundred years ago (and even more recently in some cases) when it was desirable to convey water from a source to point of use, the designer was faced with only two issues. First, a source of fresh water had to be found. Next, if the source were found and determined suitable for whatever need required, a means of conveying the water to point of use was needed.

In designing an early water conveyance system, gravity was the key player. This point is clear when you consider that before the advent of the pump, a motive force to power the pump, and the energy required to provide power to the motive force were developed, gravity was the means by which water was conveyed (with the exception of burdened humans and animals that physically carried the water) from one location to another.

Early gravity conveyance systems employed the use of clay pipe, wood pipe, natural gullies or troughs, aqueducts fashioned from stone, and any other means that was suitable or available to convey the water. Some of these earlier pipe or conveyance materials are still in use today.

With the advent of modern technology (electricity, the electric motor, the pump and various machines and processes) and the need to convey fluids other than water, also came the need to develop piping materials that could carry a wide variety of fluids.

The modern waterworks has a number of piping systems made up of different materials. One of the principal materials used in piping systems is metal. Metal pipes may be made of cast iron, stainless steel, brass, copper, and various alloys. As a waterworks or wastewater maintenance operator who works with metal piping, you must be knowledgeable about the characteristics of individual metals as well as the kinds of considerations common to all piping systems. These considerations include the effect of temperature changes, impurities in the line, shifting of pipe supports, corrosion, and water hammer.

In this section, we present information about pipes made of cast iron, steel, copper, and other metals. We also

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discuss the behavior of fluids in a piping system, and the methods of connection sections of pipe.

8.3.4.1 Characteristics of Metallic Materials

Different metals have different characteristics, making them usable in a wide variety of applications. Metals are divided into two types: ferrous, which includes iron and iron-base alloys (a metal made up of two or ore metals which dissolve into each other when melted together); and nonferrous, which covers other metals and alloys.

Important Point: Mixing a metal and a nonmetal (e.g., steel, which is a mixture of iron (a metal) and carbon (a non-metal) can also form an alloy.

Metallurgy (the science and study of metals) deals with the extraction of metals from ores and with the combining, treating, and processing of metals into useful materials.

A ferrous metal is one that contains iron (elemental symbol Fe). Iron is one of the most common of metals, but is rarely found in nature in its pure form. Comprising about 6% of the earth's crust, iron ore is actually in the form of iron oxides (Fe_2O_3 or Fe_3O_4). Coke and limestone are used in reduction of iron ore in a blast furnace where oxygen is removed from the ore, leaving a mixture of iron and carbon and small amounts of other impurities. The end product removed from the furnace is called pig iron — an impure form of iron. Sometimes the liquid pig iron is cast from the blast furnace and used directly for metal castings. However, the iron is more often remelted in a furnace, to further refine it and adjust its composition.[10]

Important Note: Piping is commonly made of wrought iron, cast iron, or steel. The difference among them is largely the amount of carbon that each contains.

Remelted pig iron is known as cast iron (meaning the iron possesses carbon in excess of 2% weight). Cast iron is inferior to steel in malleability, strength, toughness, and ductility (i.e., it is hard and brittle). Cast iron has, however, better fluidity in the molten state and can be cast satisfactorily into complicated shapes.

Steel is an alloy of iron with no more than 2.0% by weight carbon. The most common method of producing steel is to refine pig iron by oxidation or impurities and excess carbon, both of which have a higher affinity for oxygen than iron. Stainless steel is an alloy of steel and chromium.

Important Note: When piping is made of stainless steel, an "S" identifies it after the schedule number.

Various heat treatments can be used to manipulate specific properties of steel, such as hardness and ductility (meaning it can be fashioned into a new form without breaking). One of the most common heat treatments employed in steel processing is annealing. Annealing (sometimes referred to as stress-relieving) consists of heating the metal and permitting it to cool gradually to make it softer and less brittle.

Important Point: Steel is one of the most important basic production materials of modern industry.

Unlike ferrous metals, nonferrous metals do not contain iron. A common example of a nonferrous metal used in piping is brass. Other examples of nonferrous materials used in pipe include polyethylene, polybutylene, polyurethane, and PVC. Pipes[11] of these materials are commonly used in low-pressure applications for transporting coarse solids.

In addition to the more commonly used ferrous and nonferrous metals, special pipe materials for special applications are also gaining wider use in industry, even though they are more expensive. Probably one of the most commonly used materials that falls into this category is aluminum pipe. Aluminum pipe has the advantage of being lightweight and corrosion-resistant with relatively good strength characteristics.

Important Note: Although aluminum is relatively strong, it is important to note that its strength decreases as temperature increases.

Lead is another special pipe material used for certain applications, especially where a high degree of resistance to corrosive materials is desired. Tantalum, titanium, and zirconium piping materials are also highly resistant to corrosives.

Piping systems convey many types of water, including service water, city water, treated or processed water, and distilled water. Service water, used for flushing and cooling purposes, is untreated water that is usually strained, but is otherwise raw water taken directly from a source (e.g., lake, river, or deep well). City water is treated potable water. Treated water has been processed to remove various minerals that could cause deterioration or sludge in piping. Distilled water is specially purified.

Important Point: Piping materials selection for use in water treatment and distribution operations should be based on commonly accepted piping standards such as those provided by ASTM, AWWA, ANSI, the American Society of Mechanical Engineers, and the American Petroleum Industry.

8.3.4.1.1 Cast-Iron Pipe

According to AWWA, "there are more miles of [cast-iron pipe] in use today than of any other type. There are many water systems having cast-iron mains that are over 100 years old and still function well in daily use."[12] The advantages of cast-iron pipe are that it is strong, has a

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long service life, and is reasonably maintenance-free. The disadvantages include its being subject to electrolysis and attack from acid and alkali soils and its heaviness.[13]

8.3.4.1.2 Ductile-Iron Pipe

Ductile-iron pipe resembles cast-iron pipe in appearance and has many of the same characteristics. It differs from cast-iron pipe in that the graphite in the metal is spheroidal or nodular form —in ball-shape form rather than in flake form. Ductile-iron pipe is strong, durable, has high flexural strength and good corrosion resistance, is lighter than cast iron, has greater carrying capacity for same external diameter, and is easily tapped. However, ductile-iron pipe is subject to general corrosion if installed unprotected in a corrosive environment.[14]

8.3.4.1.3 Steel Pipe

Steel pipe is sometimes used as large feeder mains in water-distribution systems. It is frequently used where there is particularly high pressure or where very large diameter pipe is required. Steel pipe is relatively easy to install; has high tensile strength, lower cost, and is good hydraulically when lined; and is adaptable to locations where some movement may occur. However, it is subject to electrolysis external corrosion in acid or alkali soil, and has poor corrosion-resistance unless properly lined, coated, and wrapped.

Note: The materials of which street wastewater (sewer) pipes are most commonly constructed are vitrified clay pipe, plastic, concrete, and ductile iron pipe. However, it is metallic ductile iron pipe that is most commonly used in wastewater collection, primarily for force mains (interceptor lines, etc) and for piping in and around buildings. Ductile iron pipe is generally not used for gravity sewer applications, however.

8.3.5 Maintenance Characteristics of Metallic Piping

Maintenance of metallic piping is determined in part by characteristics of the metal (i.e., expansion, flexibility, and support), but also includes the kind of maintenance common to nonmetallic piping systems as well. The major considerations are:

1. Expansion and flexibility
2. Pipe support systems
3. Valve selection
4. Isolation
5. Backflow prevention
6. Water hammer
7. Air binding
8. Corrosion effects

8.3.5.1 Expansion and Flexibility

Because of thermal expansion, water and wastewater systems (which are rigid, and laid out in specified lengths) must have adequate flexibility. In water and wastewater systems without adequate flexibility, thermal expansion may lead to failure of piping or anchors. It may also lead to joint leakage and excessive loads on appurtences. The thermal expansion of piping can be controlled by use of proper locations of anchors, guides, and snubbers. Where expansion cannot be controlled, flexibility is provided by use of bends, loops, or expansion joints.[15]

Important Point: Metals expand or contract according to temperature variations. Over a long run (length of pipe), the effects can cause considerable strain on the lines — damage or failure may result.

8.3.5.2 Pipe Support Systems

Pipe supports are normally used to carry dead weight and thermal expansion loads. These pipe supports may loosen in time, so they require periodic inspection. Along with normal expansion and contraction, vibration (water hammer and/or fluids traveling at high speeds and pressures) can cause the supports to loosen.

8.3.5.3 Valve Selection

Proper valve selection and routine preventive maintenance is critical in the proper operation and maintenance of any piping system. In water and wastewater-piping systems, valves are generally used for isolating a section of a water main or wastewater collection line, draining the water or wastewater line, throttling liquid flow, regulating water or wastewater storage levels, controlling water hammer, bleeing off of air, or preventing backflow.

8.3.5.4 Isolation

Various valves are used in piping systems to provide for isolation. For instance, gate valves are used to isolate specific areas (valve closed) of the system during repair work or to reroute water/wastewater flow (valve open) throughout the distribution or collection system. Service stop valves are commonly used to shut off service lines to individual homes or industries. Butterfly valves are also used for isolation purposes.

8.3.5.5 Preventing Backflow

Backflow, or reversed flow, could result in contaminated or polluted water entering the potable water system. There are numerous places in a water distribution system where unsafe water may be drawn into the potable water mains if a temporary vacuum should occur in the system. In

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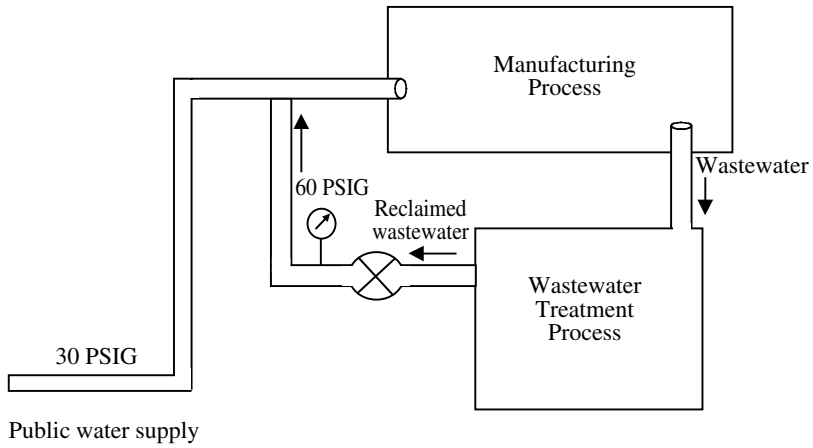

FIGURE 8.4 Shows backflow from recirculated system. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

addition, contaminated water from a higher-pressure source can be forced through a water system connection that is not properly controlled. A typical backflow condition from recirculated system is illustrated in Figure 8.4.

Important Point: Valves, air gaps, reduced-pressure-zone backflow preventers, vacuum breakers, and barometric loops are often used as backflow-prevention devices, depending on the situation.

8.3.5.6 Water Hammer

In water and wastewater operations specifically involving flow through piping, we often hear the term water hammer used. The term water hammer (often called surging) is actually a misnomer in that it implies only water and the connotation of a hammering noise. However, it has become a generic term for pressure wave effects in liquids.

By definition, water hammer is a pressure (acoustic) wave phenomenon created by relatively sudden changes in the liquid velocity. In pipelines, sudden changes in the flow (velocity) can occur as a result of (1) pump and valve operation in pipelines, (2) vapor pocket collapse, or (3) even the impact of water following the rapid expulsion of air out of a vent or a partially open valve.[16] Water hammer can damage or destroy piping, valves, fittings, and equipment.

Important Point: When water hammer occurs, there is little the maintenance operator can do except to repair any damage that results.

8.3.5.7 Air Binding

Air enters a piping system from several sources. These include air being released from the water, air being carried in through vortices into the pump suction, air leaking in through joints that may be under negative pressure, and air being present in the piping system before it is filled. The problem with air entry or air binding, because of air accumulation in piping, is that the effective cross-sectional area for water/wastewater flow in piping is reduced. This flow reduction can, in turn, lead to an increase in pumping costs through the resulting extra head loss.

8.3.5.8 Corrosion Effects

All metallic pipes are subject to corrosion. Many materials react chemically with metal piping to produce rust, scale, and other oxides. In regards to water treatment processes, when raw water is taken from wells, rivers, or lakes, the water solution is an extremely dilute liquid of mineral salts and gases. The dissolved mineral salts are a result of water flowing over and through the earth layers. The dissolved gases are atmospheric oxygen and carbon dioxide that are picked up by water-atmosphere contact. Wastewater picks up corrosive materials mainly from industrial processes and/or from chemicals added to the wastewater during treatment.

Important Point: Materials such as acids, caustic solutions, and similar solutions are typical causes of pipe corrosion.

There are several types of corrosion to be considered in water and wastewater distribution or collection piping systems:[17]

1. Internal corrosion — caused by aggressive water flowing through the pipes
2. External corrosion — caused by the soil's chemical and electrical conditions
3. Bimetallic corrosion — caused when components made of dissimilar metals are connected
4. Stray-current corrosion — caused by uncontrolled DC electrical currents flowing in the soil

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8.3.6 Joining Metallic Pipe

According to Crocker, pipe joint design and selection can have a major impact on the initial cost, long-range operating cost, and the performance of the piping system. When determining the type of joint to be used in connecting pipe, certain considerations must be made. For example, initial considerations include: material cost, installation labor cost, and degree of leakage integrity required. The operator is also concerned with periodic maintenance requirements, and specific performance requirements.[18]

Metallic piping can be joined or connected in a number of ways. The method used depends on: (1) the nature of the metal sections (ferrous, nonferrous) being joined, (2) the kind of liquid or gas to be carried by the system, (3) pressure and temperature in the line, and (4) access requirements.

A joint is defined simply as the connection between elements in a piping system. At present, there are five major types of joints, each used for a special purpose, used for joining metal pipe: (see Figure 8.5)

1. Bell-and-spigot joints
2. Screwed or threaded joints
3. Flanged joints
4. Welded joints
5. Soldered joints

8.3.6.1 Bell-and-Spigot Joints

The bell-and-spigot joint has been around since its development in the late 1780s. The joint is used for connecting lengths of cast iron water and wastewater pipe (gravity flow only). The bell is the enlarged section at one end of the pipe; the plain end is the spigot (see Figure 8.5). The spigot end is placed into the bell, and the joint is sealed. The joint sealing compound is typically made up with lead and oakum. Lead and oakum constitute the prevailing joint sealer for sanitary systems. Bell-and-spigot joints are usually reserved for sanitary sewer systems; they are no longer used in water systems.

Important Point: Bell-and-spigot joints are not used in ductile iron pipe.

8.3.6.2 Screwed or Threaded Joints

Screwed or threaded joints (see Figure 8.5) are commonly used to join sections of smaller-diameter low pressure pipe; they are used in low-cost, noncritical applications such as domestic water, industrial cooling, and fire protection systems. Diameters of ferrous or nonferrous pipe joined by threading range from 1/8 to 8 in. Most couplings have threads on the inside surface. The advantages of this type of connection are its relative simplicity, ease of installation (where disassembly and reassembly are necessary to accommodate maintenance needs or process changes), and high leakage integrity at low pressure and temperature where vibration is not encountered. Screwed construction is commonly used with galvanized pipe and fittings for domestic water and drainage applications.

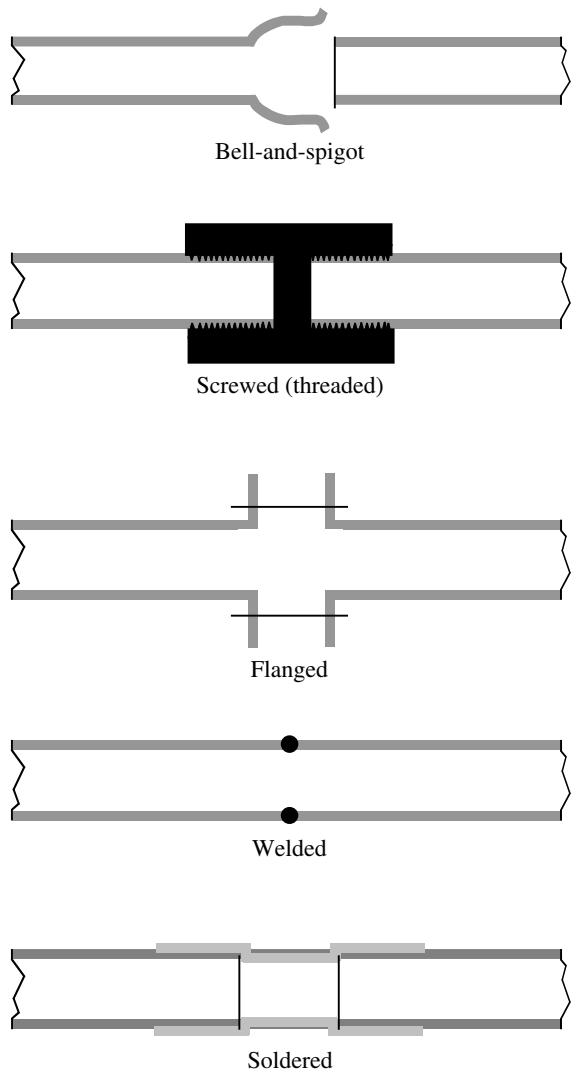

FIGURE 8.5 Common pipe joints. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Important Point: Maintenance supervisors must ensure that screwed or threaded joints are used within the limitations imposed by the rules and requirements of the applicable code.

8.3.6.3 Flanged Joints

As shown in Figure 8.6, flanged joints consist of two machined surfaces that are tightly bolted together with a gasket between them. The flange is a rim or ring at the end of the fitting, which mates with another section. Flanges are

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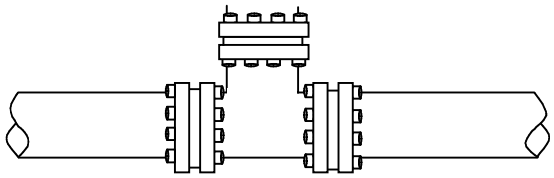

FIGURE 8.6 Flanged assembly. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

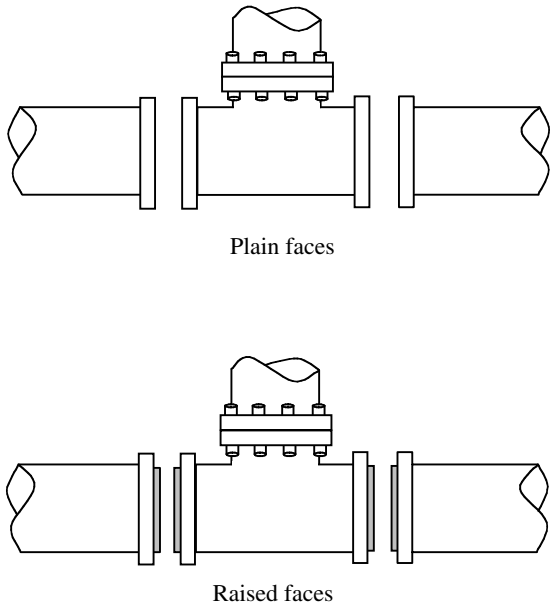

FIGURE 8.7 Flange faces. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

joined either by being bolted together or welded together. Some flanges have raised faces and others have plain faces, as shown in Figure 8.7. Steel flanges generally have raised faces, and iron flanges usually have plain or flat faces.

Important Point: A flange with a raised face should never be joined to one with a plain face.

Flanged joints are used extensively in water and wastewater piping systems because of their ease of assembly and disassembly, but they are expensive. Contributing to the higher cost are the material costs of the flanges and the labor costs for attaching the flanges to the pipe and then bolting the flanges each other.[19] Flanged joints are not normally used for buried pipe because of their lack of flexibility to compensate for ground movement. Instead, flanged joints are primarily used in exposed locations where rigidity, self-restraint, and tightness are required (e.g., inside treatment plants and pumping stations).

8.3.6.4 Welded Joints

For applications involving high pressures and temperatures, welded joints are preferred. Welding of joints is the

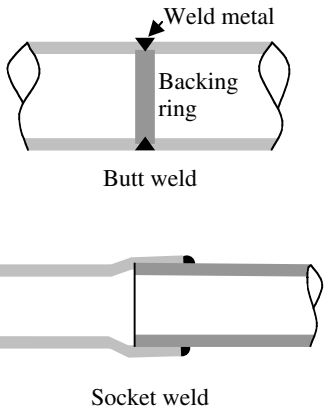

FIGURE 8.8 Two kinds of welding pipe joints. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

process whereby metal sections to be joined are heated to such a high temperature that they melt and blend together. The advantage of welded joints is obvious: the pieces joined become one continuous piece. When a joint is properly welded, the joint is as strong as the piping.

There are two basic types of welded joints are (see Figure 8.8):

1. Butt-welded joints — With these joints, the sections to be welded are placed end-to-end. This is the most common method of joining pipe used in large industrial piping systems.
2. Socket-welded joints — With these joints, one pipe fits inside the other, the weld being made on the outside of the lap. They are used in applications where leakage integrity and structural strength are important.

8.3.6.5 Soldered and Brazed Joints

Soldered and brazed joints are most often used to join copper and copper-alloy (non-ferrous metals) piping systems, although brazing of steel and aluminum pipe and tubing is possible. The main difference between brazing and welding is the temperatures employed in each process. Brazing is accomplished at far lower temperatures, but requires higher temperatures than soldering. In both brazing and soldering, the joint is cleaned (using emery cloth) and then coated with flux that prevents oxides from forming. The clean, hot joint draws solder or brazing rod (via capillary action) into the joint to form the connection. The parent metal does not melt in brazed or soldered construction.

8.4 NONMETALLIC PIPING

Although metal piping is widely used today, nonmetallic piping (especially clay and cement) is of equal importance.

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New processes to make them more useful in meeting today's requirements have modified these older materials.

However, relatively speaking, using metallic piping is a new practice. All piping was originally made from clay or wood, and stone soon followed. Open stone channels or aqueducts were used to transport water over long distances. After nearly 2000 years of service, some of these open channels are still in use today.

Common practice today is to use metal piping, though nonmetallic piping is of equal importance and has many applications in water and wastewater operations. Many of the same materials that have been used for centuries (e.g., clay) are still used today, but now many new piping materials are available; the choice depends on the requirements of the planned application. The development of new technological processes has enabled the modification of older materials for new applications in modern facilities, and has brought about the use of new materials for old applications as well.

In this section, we study nonmetallic piping materials — what they are, and where they are most commonly used. We also describe how to join sections of nonmetallic piping, and how to maintain them.

8.4.1 Nonmetallic Piping Materials

Nonmetallic piping materials used in water and wastewater applications include clay (wastewater), concrete (water and wastewater), asbestos-cement pipe (water and wastewater), and plastic (water and wastewater). Other nonmetallic piping materials include glass (chemical porcelain pipe) and wood (continuous-strip wooden pipes for carrying water and waste chemicals are used in some areas, especially in the western part of the U.S.). These materials are not discussed in this text because of their limited application in water and wastewater operations.

Important Point: As with the use of metallic piping, nonmetallic piping must be used in accordance with specifications established and codified by a number of engineering societies and standards organizations. These codes were devised to help ensure personnel safety and protection of equipment.

8.4.1.1 Clay Pipe

Clay pipes are used to carry and collect industrial wastes, wastewater, and storm water (they are not typically used to carry potable water). Clay pipes typically range in size from 4 to 36 in. in diameter, and are available in various grades and strengths.

Clay pipe is used in nonpressurized systems. For example, when used in drainpipe applications, liquid flow is solely dependent on gravity; that is, it is used as an open-channel pipe, whether partially or completely filled.

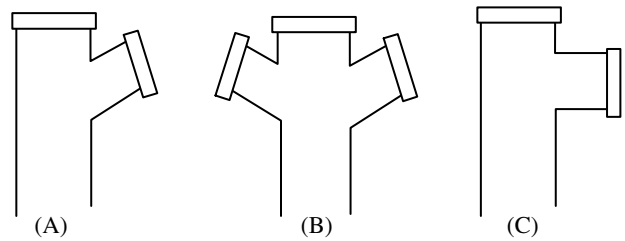

FIGURE 8.9 Section of bell-and-spigot fittings for clay pipe: (A) wye; (B) double wye; (C) tee. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

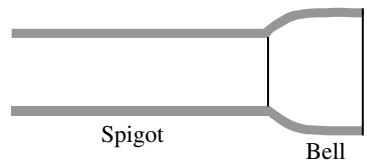

FIGURE 8.10 Bell and spigot ends of clay pipe sections. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Clay pipe is manufactured in two forms: vitrified (glass-like) and unglazed (not glassy)

Important Point: Vitrified clay pipe is extremely corrosion proof. It is ideal for many industrial waste and wastewater applications.

Important Point: McGhee recommends that wyes and tees (see Figure 8.9) should be used for joining various sections of wastewater piping. Failure to provide wyes and tees in common wastewater lines invites builders to break the pipe to make new connections. Obviously, this practice should be avoided, because such breaks are seldom properly sealed and can be a major source of infiltration.[20]

Both vitrified and unglazed clay pipe is made and joined with the same type of bell-and-spigot joint described earlier. The bell-and-spigot shape is shown in Figure 8.10. In joining sections of clay pipe, both ends of the pipe must first be thoroughly cleaned. The small (spigot) end of the pipe must be centered properly, and then seated securely in the large (bell) end. The bell is then packed with fibrous material (usually jute) for solid joints, which is tamped down until about 30% of the space is filled. The joint is then filled with sealing compound. In flexible joint applications, the sealing elements are made from natural or synthetic rubber or a plastic-type material.

Drainage and wastewater collection lines designed for gravity flow are laid downgrade at an angle, with the bell ends of the pipe pointing upgrade. The pipe is normally placed in a trench with strong support members (along its small dimension and not on the bell end). Vitrified clay

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pipe can be placed directly into a trench and covered with soil. However, unglazed clay pipe must be protected against the effects of soil contaminants and ground moisture.

8.4.1.2 Concrete Pipe

Concrete is another common pipe material, and is sometimes used for sanitary sewers in locations where grades, temperatures, and wastewater characteristics prevent corrosion.[21] The pipe provides both high tensile and compressive strength and corrosion resistance.

Concrete pipe is generally found in three basic forms: (1) nonreinforced concrete pipe; (2) reinforced concrete, cylinder, and non-cylinder pipe; and (3) reinforced and prestressed concrete pressure pipe.

With the exception of reinforced and prestressed pressure pipe, most concrete pipe is limited to low-pressure applications. Moreover, almost all-concrete piping is used for conveying industrial wastes, wastewater, and storm water; similarly, some is used for water service connections.

Rubber gaskets are used to join sections of many nonreinforced concrete pipe. However, for circular concrete sewer and culvert pipe, flexible, watertight, rubber joints are used to join pipe sections.

The general advantages of concrete pipe include the following:

1. It is relatively inexpensive to manufacture.
2. It can withstand relatively high internal pressure or external load.
3. It is highly resistant to corrosion (internal and external).
4. When installed properly, it generally has a very long, trouble-free life.
5. There are minimal bedding requirements during installation.

Disadvantages of concrete pipe include:

1. It is very heavy, and thus expensive, when shipped long distances.
2. Its weight makes special handling equipment necessary.
3. The exact pipes and fittings must be laid out in advance for installation.[22]

8.4.1.2.1 Nonreinforced Concrete Pipe

Nonreinforced concrete pipe, or ordinary concrete pipe, is manufactured in from 4- to 24-in. diameters. As in vitrified clay pipe, nonreinforced concrete pipe is made with bell-and-spigot ends. Nonreinforced concrete pipe is normally used for small wastewater (sewer) lines and culverts.

8.4.1.2.2 Reinforced Concrete Pipe

All concrete pipe made in sizes larger that 24 in. is reinforced, but reinforced pipe can also be obtained in sizes as small as 12 in. Reinforced concrete pipe is used for water conveyance (cylinder pipe), carrying wastewater, stormwater, and industrial wastes. It is also used in culverts. It is manufactured by wrapping high-tensile strength wire or rods about a steel cylinder that has been lined with cement mortar. Joints are either bell-and-spigot or tongue- and groove in sizes up to 30 in., and tongue-and-groove is exclusively above that size.

8.4.1.2.3 Reinforced and Prestressed Concrete Pipe

When concrete piping is to be used for heavy load high-pressure applications (up to 600 psi), it is strengthened by reinforcement and prestressing. Prestressed concrete pipe is reinforced by steel wire, steel rods, or bars embedded lengthwise in the pipe wall. If wire is used, it is wound tightly to prestress the core and is covered with an outer coating of concrete. Prestressing is accomplished by manufacturing the pipe with a permanent built-in compression force.

8.4.1.2.4 Asbestos Cement Pipe

Before beginning a brief discussion of asbestos-cement (A-C) pipe, it is necessary to discuss safety and health implications involved with performing maintenance activities on A-C pipe.

Prior to 1971, asbestos was known as the "material of a thousand uses."[23] It was used for fireproofing (primarily), insulation (secondarily, on furnaces, ducts, boilers and hot water pipes, for example), soundproofing, and a host of other applications, including its use in conveyance of water and wastewater. However, while still used in some industrial applications and in many water and wastewater-piping applications, asbestos containing materials (ACM), including A-C pipe, are not as widely used as they were before 1971.

Asbestos containing materials lost favor with regulators and users primarily because of the health risks involved. Asbestos has been found to cause chronic and often-fatal lung diseases, including asbestosis and certain forms of lung cancer. Although debatable, there is some evidence that asbestos fibers in water may cause intestinal cancers as well. It is true that asbestos fibers are found in some natural waters[24] and can be leached from asbestos cement pipe by very aggressive waters (i.e., those that dissolve the cement[25]). However, it is also true that the danger from asbestos exposure is not so much due to the danger of specific products (e.g., A-C pipe) as it is to the overall exposure of people involved in the mining, production, installation, and ultimate removal and disposal of asbestos products.[26]

A-C pipe is composed of a mixture of Portland cement and asbestos fiber, which is built up on a rotating steel

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mandrel and then compacted with steel pressure rollers. This pipe has been used for over 70 years in the U.S. Because it has a very smooth inner surface, it has excellent hydraulic characteristics.[27]

In water and wastewater operations, it is the ultimate removal and disposal of asbestos cement pipe that poses the problem for operators. For example, consider an underground wastewater line-break that must be repaired. After locating exactly where the line-break is (sometimes difficult to accomplish, because A-C pipe is not as easily located as conventional pipe), the work crew must first excavate the soil covering the line-break, being careful not to cause further damage since A-C pipe is relatively fragile. Once the soil has been removed, exposing the line-break, the damaged pipe section must be removed. In some instances, it may be more economical or practical to remove the damaged portion of the pipe only, and to install a replacement portion and then girdle it with a clamping mechanism (sometimes referred to as a *saddle-clamp*).

To this point in the described repair operation, there is little chance for exposure to personnel from asbestos. In order to be harmful, ACM must release fibers that can be inhaled. The asbestos in undamaged A-C pipe is not friable (nonfriable asbestos); it cannot be readily reduced to powder form by hand pressure when it is dry. Thus, it poses little or no hazard in this condition. However, if the maintenance crew making the pipe repair must cut, grind, or sand the A-C pipe section under repair, the non-friable asbestos is separated from its bond. This type of repair activity is capable of releasing friable airborne fibers — this is the hazard of working with A-C pipe.

To guard against the hazard of exposure to asbestos fibers, A-C pipe repairs must be accomplished in a safe manner. Operators must avoid any contact with ACM that disturbs its position or arrangement, disturbs its matrix or renders it friable, and generates any visible debris from it.

Important Point: Visibly damaged, degraded, or friable ACM in the vicinity are always indicators that surface debris or dust could be contaminated with asbestos. Occupational Health and Safety Administration standards require that we assume that such dust or debris contains asbestos fibers.[28]

In the A-C pipe repair operation described above, repairs to the A-C pipe require that prescribed U.S. Environmental Protection Agency (EPA), Occupational Health and Safety Administration (OSHA), state, and local guidelines be followed. General EPA/OSHA guidelines, at a minimum, require that trained personnel perform repairs made to the A-C pipe, only. The following safe work practice is provided for those who must work on or with ACM (i.e., A-C pipe).

8.4.1.2.4.1 Safe Work Practice: A-C Pipe[29]

1. When repairs/modifications are conducted that require cutting, sanding, or grinding on cement pipe containing asbestos, EPA-trained asbestos workers or supervisors are to be called to the work site immediately.
2. Excavation personnel will unearth buried pipe to the point necessary to make repairs or modifications. The immediate work area will then be cleared of personnel as directed by the asbestos-trained supervisor.
3. The on-scene supervisor will direct the asbestos-trained workers as required to accomplish the work task.
4. The work area will be barricaded 20 ft in all directions to prevent unauthorized personnel from entering.
5. Asbestos-trained personnel will wear all required Personal Protective Equipment (PPE). Required PPE shall include Tyvek totally enclosed suits, 1/2 face respirator equipped with HEPA filters, rubber boots, goggles, gloves, and hard hats.
6. Supervisor will perform the required air sampling before entry.
7. Air sampling shall be conducted using National Institute for Occupational Safety and Health (NIOSH) 7400 Protocol.
8. A portable decontamination station will be set up as directed by supervisor.
9. Workers will enter the restricted area only when directed by the supervisors and, using wet methods *only*, will either perform pipe cutting using a rotary cutter assembly or inspect the broken area to be covered with repair saddle device.
10. After performing the required repair or modifications, workers will encapsulate bitter ends and fragmented sections.
11. After encapsulation, the supervisor can authorize entry into restricted area for other personnel.
12. Broken ACM pipe pieces must be properly disposed of following EPA, state, and local guidelines.

Important Point: Although exposure to asbestos fibers is dangerous, it is important to note that studies by EPA, AWWA, and other groups have concluded that the asbestos in water mains does not generally constitute a health threat to the public.[30]

Because A-C pipe is strong and corrosion resistant, it is widely used for carrying water and wastewater. Standard sizes range from 3 to 36 in. Though highly resistant to corrosion, A-C pipe should not be used for carrying highly acid solutions or unusually soft water, unless its inner and

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outer surface walls are specially treated. A-C pipe is preferred for use in many outlying areas because of its light weight, which results in greater ease of handling.

Using an asbestos-cement sleeve joins A-C pipe. The sleeve's I.D. is larger than the pipe's O.D. The ends of the pipes fit snugly into the sleeve and are sealed with a natural or synthetic rubber seal or gasket, which acts as an expansion joint.

8.4.1.3 Plastic Pipe

Plastic pipe has been used in the U.S. for about 60 years; its use is becoming increasingly common. In fact, because of its particular advantages, plastic pipe is replacing both metallic and nonmetallic piping. The advantages of plastic piping include:

1. Internal and external high corrosion resistance
2. Rarely needs to be insulated or painted
3. Lightweight
4. Ease of joining
5. Freedom from rot and rust
6. Will not burn (readily)
7. Lower cost
8. Long service life
9. Easy to maintain

There are several types of plastic pipe. Plastic pipe is commonly used in water and wastewater service, but PVC is the most common plastic pipe for municipal water distribution systems.

PVC is a polymer extruded (shaped by forcing through a die) under heat and pressure into a thermoplastic that is nearly inert when exposed to most acids, fuels, and corrosives. PVC is commonly used to carry cold drinking water, because it is nontoxic and will not affect the water's taste or cause odor.

The limitations of PVC pipe include its limited temperature range (approximately 150 to 250° F) and low-pressure capability (usually 75 to 100 psi).

Joining sections of plastic pipe is accomplished by welding (solvent, fusion, fillet), threading, and flanges.

Important Point: The strength of plastic piping decreases as the temperature of the materials it carries increases.

8.5 TUBING

Piping by Another Name Might be Tubing?

A logical question might be, when is a pipe a tube, or a tube a pipe?. Does it really matter if we call piping or tubing by two distinct, separate, and different names? It depends, of course, on the differences between the two.

When we think of piping and tubing, we think of tubular, which infers cylindrical products that are hollow. Does this description help us determine the difference between piping and tubing? No, not really. We need more — a more concise description or delineation.

Maybe size will work. It is true that when we normally think of pipe, we think in terms of either metallic or nonmetallic cylindrical products that are hollow and range in nominal size from about 0.5 inch (or less) to several feet in diameter. On the other hand, when we think of tubing we think of cylindrical, hollow products that are relatively smaller in diameter than that of many piping materials.

Maybe application will work. It is true that when we normally think of pipe, we think of any number of possible applications from conveying raw petroleum from field to refinery, to the conveyance of raw water from source to treatment facility, to wastewater discharge point to treatment to outfall, and several others. When we think in terms of tubing applications and products conveyed, the conveyance of compressed air, gases (including liquefied gas), steam, water, lubricating oil, fuel oil, chemicals, fluids in hydraulic systems, and waste products comes to mind.

On the surface, and evidenced by the discussion above, it is apparent that when we attempt to classify or differentiate piping and tubing, our effort is best characterized as somewhat arbitrary, capricious, vague, and ambiguous. It appears that piping by any other name is just piping. In reality, piping is not tubing, and in the end (so to speak) the difference may come down to determination by end use.

The bottom line is that it is important to differentiate between piping and tubing because they are different. They are different in physical characteristics and methods of installation, as well as in their advantages and disadvantages. In this chapter, these differences become clear.

8.5.1 Tubing vs. Piping: The Difference

Lohmeier and Avery point out that piping and tubing are considered separate products, even though they are geometrically quite similar. Moreover, the classification of pipe or tube is determined by end use.[31]

As mentioned, many of the differences between piping and tubing are related to physical characteristics, methods of installation, and the advantages and disadvantages.

8.5.1.1 Tubing

Simply, tubing refers to tubular materials (products) made to either an I.D. or O.D. (expressed in even inches or fractions). Tubing walls are generally much thinner than those of piping; thus, wall thickness in tubing is of particular importance.

Important Point: Wall thickness tolerance in tubing is held so closely that wall thickness is usually

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given in thousandths of an inch rather than as a fraction of an inch. Sometimes a gauge number is used to indicate the thickness according to a given system.

Tubing of different diameters has different wall thickness. An example from "Pipe Properties" and "Tubing Properties" illustrates the difference between piping and tubing.[32] The wall thickness of a commercial type of 8-in. pipe is 0.406 in. Light-wall 8-in. copper tubing, by contrast, has a wall thickness of 0.050 in. When we compare these figures, it is clear that tubing has much thinner walls than piping of the same general diameter.

Important Note: It is important to note that the range between thick and thin is narrower for tubing than it is for piping.

The list of tubing applications is a lengthy one. Some tubing types can be used not only as conduits for electrical wire, but also used to convey waste products, compressed air, hydraulic fluids, gases, fuel oil, chemicals, lubricating oil, stream, waters, and other fluids (i.e., both gaseous and liquid).

Tubing is made from both metals and plastics. Metal tubing is designed to be somewhat flexible but also strong. Metallic materials such as copper, aluminum, steel, and stainless steel are used in applications where fluids are carried under high pressure (some types of tubing [e.g., stainless steel] can accommodate very high pressures [>5000 psi]). As the diameter of the tubing increases, the wall thickness increases accordingly (slightly).

Ranging in size from 1/32 to 12 in. in diameter, it is the smaller sizes that are most commonly used. Standard copper tubing ranges from 1/32 to 10 in. in diameter, steel ranges from 3/15 in. to 10¾ in., aluminum ranges from 1/8 to 12 in., and special alloy tubing is available up to 8 in. in diameter.

One of the primary reasons tubing is employed for industrial applications is the fact that some tubing materials are extremely resistant to deterioration by corrosive chemicals.

Typically, in terms of initial cost, metal tubing materials are more expensive than iron piping. However, high initial cost vs. ability to do a particular application as designed (or desired), is a consideration that cannot be overlooked or underemphasized. Consider, for example, an air compressor. Typically, while in operation, air compressors are mechanical devices that not only produce a lot of noise, but also vibrate. Installing a standard rigid metal piping system to such a device might not be practical. Installing tubing that is flexible to the same device, however, may have no detrimental impact on operation whatsoever. An even more telling example is the internal combustion engine. For example, a lawnmower engine, like the air compressor, also vibrates and is used in less than static conditions (i.e., the lawnmower is typically exposed to all kinds of various dynamic stresses). Obviously, we would not want the fuel lines (tubing) in such a device to be hard-wired with rigid pipe; instead, we would want the fuel lines to be durable but also somewhat flexible. Thus, flexible metal tubing is called for in this application because it will hold up.

Simply put, initial cost can be important. However, considerations such as maintenance requirements, durability, length of life, and ease of installation, often favor the use of metallic tubing over the use of metallic pipe.

While it is true that most metallic tubing materials have relatively thin walls, it is also true that most are quite strong. Small tubing material with thin walls (i.e., soft materials up to approximately 1 in. O.D.) can be bent quite easily by hand. Tubing with larger diameters requires special bending tools. The big advantage of flexible tubing should be obvious: tubing can be run from one point to another with fewer fittings than if piping was used.

Note: Figure 8.11 shows how the use of tubing can eliminate several pipefittings.

The advantages of the tubing type of arrangement shown in Figure 8.11 include the following:

1. It eliminates eighteen potential sources of leaks.
2. The cost of the 18 90° elbow fittings needed for the piping installation is eliminated.
3. The time needed to cut, gasket, and flange the separate sections of pipe is conserved. (It takes little time to bend tubing into the desired configuration.)
4. A tubing configuration is much lighter in weight than the separate lengths of pipe and the pipe flanges would have been.

As mentioned, in the configuration shown in Figure 8.11, the amount of weight is considerably less for the copper tubing than the piping arrangement. Moreover, the single length of tubing bent to follow the same general conveyance route is much easier to install.

It may seem apparent to some readers that many of the weight and handling advantages of tubing compared to piping can be eliminated or at least matched simply by reducing the wall thickness of the piping. It is important to remember, that piping has a thick wall because it often needs to be threaded to make connections. For example if the wall thickness of iron pipe was made comparable to the thickness of copper tubing and then threaded at connection points, its mechanical integrity would be reduced. The point is piping must have sufficient wall thickness left after threading to not only provide a tight fit, but also to handle the fluid pressure. On the other hand, copper tubing is typically designed for brazed and soldered connections, rather than threaded ones. Thus, its

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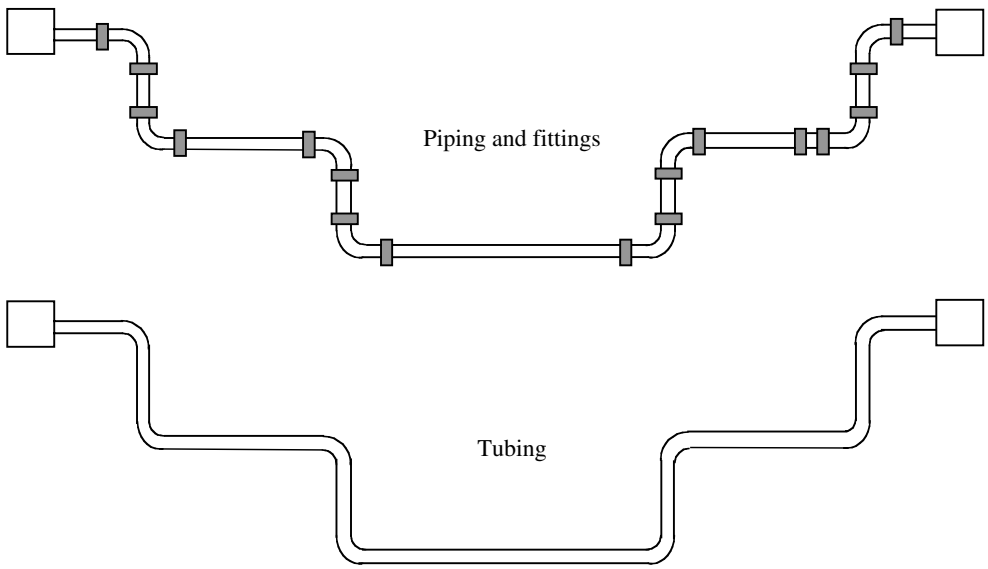

FIGURE 8.11 Tubing eliminates fittings. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

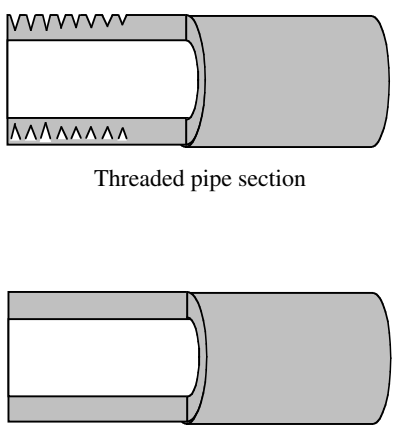

FIGURE 8.12 Pipe wall thickness is important when threading is required. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

wall thickness can be made uniformly thin. This advantage of tubing over iron piping is illustrated in Figure 8.12.

Important Point: The lighter weight of tubing means greater ease of handling, as well as lower shipping costs.

8.5.2 Advantages of Tubing

To this point, in regards to design requirements, reliability, and maintenance activities of using tubing instead of piping, we have pointed out several advantages of tubing. These advantages can be classified as mechanical and chemical advantages.

8.5.2.1 Tubing: Mechanical Advantages

Probably the major mechanical advantage of using tubing is its relatively small diameter and its flexibility. These features make it user-friendly in tight spaces where piping would be difficult to install and to maintain (i.e., for the tightening or repair or replacement of fittings).

Another mechanical advantage of tubing important to water and wastewater maintenance operators is the ability of tubing to absorb shock from water hammer. Water hammer can occur whenever fluid flow is started or stopped. In water and wastewater operations, certain fluid flow lines have a frequent on-off cycle. In a conventional piping system, this may produce vibration, which is transmitted along the rigid conduit, shaking joints, valves, and other fittings. The resulting damage usually results in leaks that need repairs. In addition, the piping supports can also be damaged. When tubing, with its built-in flexibility, is used in place of conventional iron piping, the conduit absorbs most of the vibration and shock. The result is far less wear and tear on the fittings and other appurtenances.

As mentioned, sections of tubing are typically connected by means of soldering, brazing, or welding rather than by threaded joints. However, steel tubing is sometimes joined by threading. In addition to the advantages in cost and saving time, avoidance of using threaded joints precludes other problems. For example, any time piping is threaded it is weakened. At the same time, threading is commonly used for most piping systems and usually presents no problem.

Another advantage of tubing over iron piping is the difference in inner-wall surfaces between the two. Specifically, tubing generally has a smoother inner-wall surface than iron piping. This smoother inner-wall characteristic

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aids in reducing turbulent flow (wasted energy and decreased pressure) in tubing. Instead, flow in the smoother walled tubing is more laminar; it has less turbulence. Laminar flow is characterized as flow in layers — very thin layers. (Somewhat structurally analogous to this liquid laminar flow phenomenon is wood type products such as kitchen cabinets. Many of these are constructed of laminated materials.)

This might be a good time to address laminar flow inside a section of tubing. First, we need to discuss both laminar and turbulent flow in order to point out the distinct difference between them. Simply, in *laminar* flow, streamlines remain parallel to one another and no mixing occurs between adjacent layers. In *turbulent* flow, mixing occurs across the pipe. The distinction between the two regimes lies in the fact that the shear stress in laminar flow results from viscosity. In turbulent flow the shear stress results from momentum exchanges occurring as a result of motion of fluid particles from one layer to another.[33]

Normally flow is laminar inside tubing. If there are irregularities (dents, scratches, or bumps) on the tubing's inner wall, the fluid will be forced across the otherwise smooth surface at a different velocity. This causes turbulence.

In contrast to tubing, iron piping has more irregularities along its inner walls. This inner-wall surface roughness produces turbulence in the fluid flowing along the conduit. Ultimately, this turbulence can reduce delivery rate of the piping system considerably.

8.5.2.2 Chemical Advantages

The major chemical advantage in tubing as compared to piping comes from the corrosion-resistant properties of the metals used to make the tubing. Against some corrosive fluids, most tubing materials do very well. Some metals perform better than others, depending upon the metal and the corrosive nature of the fluid.

It is important to also point out that tubing used must be compatible with the fluid being conveyed. When conveying a liquid stream from one point to another, the last thing wanted is contamination from the tubing to be added to the fluid. Many tubing conveyance systems are designed for use in food-processing operations, for example. If we were conveying raw milk to or from a unit process, we certainly would not want to contaminate the milk. To avoid such contamination, where conditions of particular sanitation are necessary, stainless steel, aluminum, or appropriate plastic tubing must be used.

8.5.3 Connecting Tubing

The skill required to properly connect metal or nonmetallic tubing can be learned by just about anyone. A certain amount of practice and experience is required to ensure the tubing is properly connected. Moreover, certain tools are required for connecting sections of tubing. The tools used to make either a soldered connection or a compression connection (where joint sections are pressed together) include:

1. Hacksaw
2. Tube cutter
3. Scraper
4. Flat file
5. Burring tool
6. Flaring tool
7. Presetting tool for flareless fittings
8. Assorted wrenches
9. Hammer
10. Tube bender

8.5.3.1 Cutting Tubing

No matter what type of connection you are making (soldered or compressed), it is important to cut the tubing cleanly and squarely. This can be accomplished using a tubing cutter. Use of a tubing cutter is recommended because it provides a much smoother cut than that made with a hacksaw. A typical tubing cutter has a pair of rollers on one side and a cutting wheel on the other. The tubing cutter is turned all the way around the tubing, making a clean cut.

Important Point: When cutting stainless steel tubing, cut the tubing as rapidly and safely as you can, with as few strokes as possible. This is necessary because as stainless steel is cut, it hardens, especially when cut with a hacksaw.

After making the tubing cut, the rough edge of the cut must be smoothed with a *burring* tool to remove the small metal chads, burrs, or whiskers. If a hacksaw is used to cut the tubing, ensure that the rough cut is filed until it is straight and square to the length of tubing.

8.5.3.2 Soldering Tubing[34]

Soldering is a form of brazing in which nonferrous filler metals having melting temperatures below 800°F (427°C) are used. The filler metal is called solder (usually a tin-lead alloy, which has a low melting point) and is distributed between surfaces by capillary action.

Whether soldering two sections of tubing together or connecting tubing to a fitting, such as an elbow, the soldering operation is the same. Using emery cloth or a wire brush, the two pieces to be soldered must first be cleaned (turned to bright metal). Clean, oxide-free surfaces are necessary to make sound soldered joints. Uniform capillary action is possible only when surfaces are completely free of foreign substances such as dirt, oil, grease, and oxide.

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Important Point: During the cleaning process care must be taken to avoid getting the prepared adjoining surfaces too smooth. Surfaces that are too smooth will prevent the filler metal (solder) from effectively wetting the joining areas.

The next step is to ensure that both the tubing outside and the fitting inside are covered with soldering flux and fitted together. When joining two tubing ends, use a sleeve. The purpose of flux is to prevent or inhibit the formation of oxide during the soldering process. The two ends are fitted into the sleeve from opposite sides. Make sure the fit is snug.

Next, heat the joint. First, heat the tubing next to the fitting then the fitting itself. When the flux beings to spread, solder should be added (this is known as *tinning*). The heat will suck the solder into the space between the tubing and the sleeve. Then heat the fitting, on an off, and apply more solder until the joint is fully penetrated.

Important Point: During the soldering operation, it is important to ensure that the heat is applied evenly around the tubing. A continuous line of solder will appear where the fitting and tubing meet at each end of the sleeve. Also, ensure that the joined parts are held so that they will not move. After soldering the connection, wash the connection with hot water to prevent future corrosion.

The heat source normally used to solder is heated using an oxyacetylene torch or some other high-temperature heat source.

When soldering it is important to remember the following points:

1. Always use the recommended flux when soldering.
2. Make sure parts to be soldered are clean and their surfaces fit closely together.
3. During the soldering process do not allow the parts to move while the solder is in a liquid state.
4. Be sure the soldering heat is adequate for the soldering job to be done, including the types of metal and the fluxes.
5. Wash the solder work in hot water to stop later corrosive action.

8.5.3.3 Connecting Flared/Nonflared Joints

In addition to being connected by brazing or soldering, tubing can also be connected by either flared or nonflared joints. Flaring is accomplished by evenly spreading the end of the tube outward, as shown in Figure 8.13. The accuracy of the angle of flare is important; it must match the angle of the fitting being connected. The flaring tool is inserted into the squared end of the tubing, and then hammered or impacted into the tube a short distance, spreading the tubing end as required.

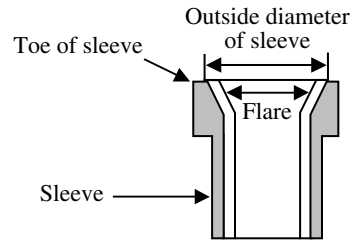

FIGURE 8.13 Flared tubing end. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

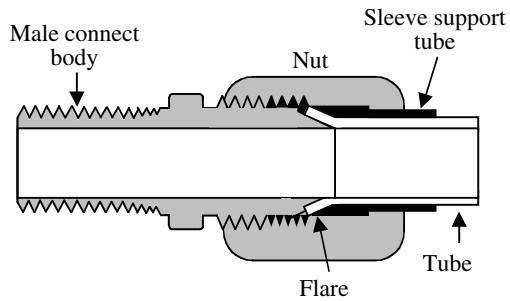

FIGURE 8.14 Flared fitting. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

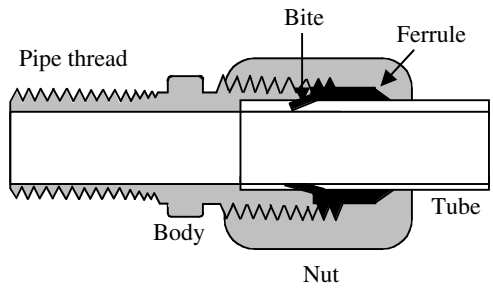

FIGURE 8.15 Flareless fitting. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

8.5.3.3.1 Flared Connection

Figure 8.14 shows the resulting flared connection. The flared section is inserted into the fitting in such a way that the flared edge of the tube rests against the angled face of the male connector body — a sleeve supports the tubing. The nut is tightened firmly on the male connector body, making a firm joint that will not leak, even if the tubing ruptures because of excess pressure.

8.5.3.3.2 Nonflared Connection

Figure 8.15 shows a flareless fitting. As shown, the plain tube end is inserted into the body of the fitting. Notice that there are two threaded outer sections with a ferrule

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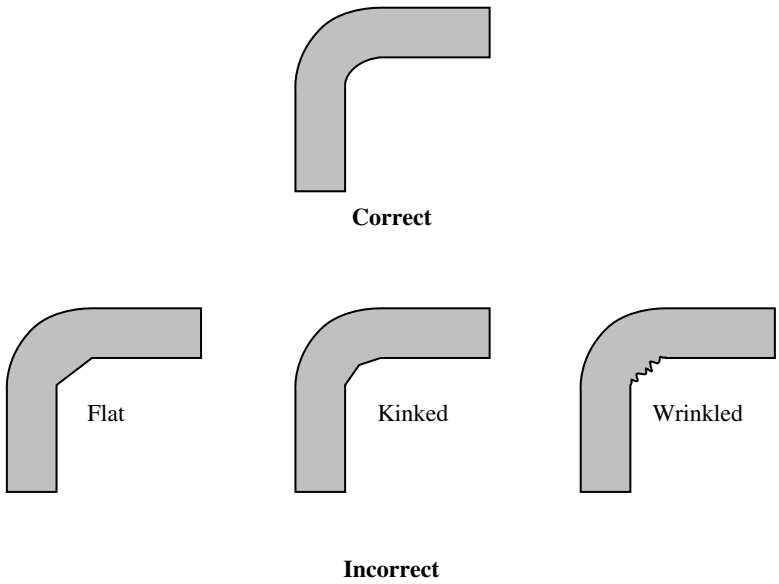

FIGURE 8.16 Correct and incorrect tubing bends. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

or bushing located between them. As the threaded members are tightened, the ferrule bites into the tubing, making a tight connection.

8.5.4 Bending Tubing

A type of tool typically used in water and wastewater maintenance applications for bending tubing is the hand bender. This is nothing more than a specifically sized-spring-type apparatus. Spring-type benders come in several different sizes (the size that fits the particular sized tubing to be bent is used to bend it). The spring-type tubing bender is slipped over the tubing section to be bent. Then, carefully, the spring and tubing are bent by hand to conform to the angle of bend desired.

In using any type of tubing bender, it is important to obtain the desired bend without damaging (flattening, kinking, or wrinkling) the tubing. As mentioned, any distortion of the smooth, inner wall of a tubing section causes turbulence in the flow, which lowers the pressure. Figure 8.16 shows three different kinds of incorrect bends and one correct bend. From the figure, it should be apparent how the incorrect bends constrict the flow, causing turbulence and lower pressure.

8.5.5 Types of Tubing

Common types of metal tubing in industrial service include:

1. *Copper* (seamless, fully annealed, furnished in coils or in straight lengths) — In water treatment applications, copper tubing has replaced lead and galvanized iron in service line installations because it is flexible, easy to install, corrosion resistant in most soils, and able to withstand high pressure. It is not sufficiently soluble in most water to be a health hazard, but corrosive water may dissolve enough copper to cause green stains on plumbing fixtures. Copper water service tubing is usually connected by either flare or compression fittings. Copper plumbing is usually connected with solder joints.[35]

Important Point: Annealing is the process of reheating a metal and then letting it cool slowly. In the production of tubing, annealing is performed to make the tubing softer and less brittle.

2. *Aluminum* (seamless, annealed, and suitable for bending and flaring)
3. *Steel* (seamless, fully annealed, also available as a welded type, suitable for bending and flaring)
4. *Stainless steel* (seamless, fully annealed, also available as a welded type, suitable for bending and flaring)
5. *Special alloy* (made for carrying corrosive materials).

Like metal piping, metal tubing is made in both welded and seamless styles. *Welded* tubing begins as flat strips of metal that is then rolled and formed into tubing. The seam is then welded.

Seamless tubing is formed as a long, hot metal ingot and then shaped into a cylindrical shape. The cylinder is then extruded (passed through a die), producing tubing in

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the larger sizes and wall thicknesses. If smaller tubing (with thinner walls and closer tolerances) is desired, the extruded tubing is reworked by drawing it through another die.

8.5.5.1 Typical Tubing Applications

In a typical water or wastewater operation, tubing is used in unit processes and machinery. Heavy-duty tubing is used for carrying gas, oxygen, steam, and oil in many underground services, interior plumbing, and heating and cooling systems throughout the plant site. Steel tubing is used in high-pressure hydraulic systems. Stainless steel tubing is used in many of their chemical systems. In addition, in many plants, aluminum tubing is used as raceways or containers for electrical wires.

Plastics have become very important as nonmetallic tubing materials. The four most common types of plastic tubing are Plexiglas (acrylic), polycarbonate, vinyl, and polyethylene.

For plant operations, plastic tubing usage is most prevalent where it meets corrosion resistance demands, and the temperatures are within its working range. It is primarily used in chemical processes.

Plastic tubing is connected either by fusing with solvent-cement or by heating. Reducing the plastic ends of the tubing to a soft, molten state, then pressing them together, makes fused joints. In the solvent-cement method, the ends of the tubing are coated with a solvent that dissolves the plastic. The tube ends are firmly pressed together, and as the plastic hardens, they are securely joined. When heat fused, the tubes are held against a hot plate. When molten, the ends are joined and the operation is complete.

8.6 INDUSTRIAL HOSES

Earlier we described the uses and merits of piping and tubing. This section describes industrial hoses, which are classified as a slightly different tubular product. Their basic function is the same — to carry fluids (liquids and gases) from one point to another.

The outstanding feature of industrial hose is its flexibility, which allows it to be used in application where vibrations would make the use of rigid pipe impossible.

Most water and wastewater treatment plants use industrial hoses to convey steam, water, air, and hydraulic fluids over short distances. It is important to point out that each application must be analyzed individually, and an industrial hose must be selected which is compatible with the system specification.

In this section, we study industrial hoses — what they are, how they are classified and constructed, and the ways in which sections of hose are connected to one another and to piping or tubing. We will also examine the maintenance requirements of industrial hoses, and what to look for when we make routine inspections or checks for specific problems.

Industrial hoses, piping, and tubing all are used to convey a variety of materials under a variety of circumstances. Beyond this similar ability to convey a variety of materials, there are differences between industrial hoses and piping and tubing. For example, in their construction and in their advantages, industrial hoses are different from piping and tubing. As mentioned, the outstanding advantage of hose is its flexibility; its ability to bend means that hose can meet the requirements of numerous applications that cannot be met by rigid piping and some tubing systems. Two examples of this flexibility are Camel hose (used in wastewater collection systems to clean out interceptor lines and to remove liquid from excavations where broken lines are in need of repair) and the hose that supplies hydraulic fluids used on many forklifts. Clearly, rigid piping would be impractical to use in both situations.

Industrial hose is not only flexible, but also has a dampening effect on vibration. Certain tools used in water and wastewater maintenance activities must vibrate to do their jobs. Probably the best and most familiar such tool is the power hammer, or jackhammer. Obviously, the built-in rigidity of piping and tubing would not allow vibrating tools to stand up very long under such conditions. Other commonly used tools and machines in water and wastewater operations have pneumatically or hydraulically driven components. Many of these devices are equipped with moving members that require the air or oil supply to move with them. In such circumstances, of course, rigid piping could not be used.

It is important to note that the flexibility of industrial hose is not the only consideration that must be taken to account when selecting hose over either piping or tubing. The hose must be selected according to the potential damaging conditions of an application. These conditions include the effects of pressure, temperature, and corrosion.

Hose applications range from the lightweight ventilating hose (commonly called elephant trunk) used to supply fresh air to maintenance operators working in manholes, vaults, or other tight places. In water and wastewater treatment plants, hoses are used to carry water, steam, corrosive chemicals and gases, and hydraulic fluids under high pressure. To meet such service requirements, hoses are manufactured from a number of different materials.

8.6.1 Hose Nomenclature

To gain a fuller understanding of industrial hoses and their applications, it is important to be familiar with the nomenclature or terminology normally associated with industrial hoses. Accordingly, in this section, we explain hose terminology with which water and wastewater operators should be familiar.

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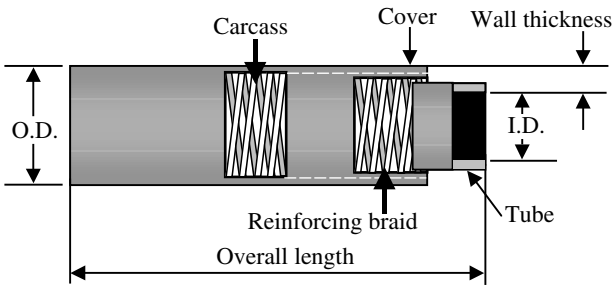

FIGURE 8.17 Common hose nomenclature. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

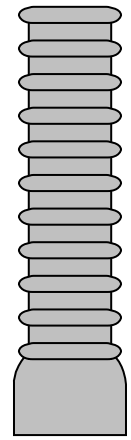

FIGURE 8.18 Expanded end hose. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Figure 8.17 is a cutaway view of a high-pressure air hose of the kind that supplies portable air hammers and drills and other pneumatic tools commonly used in water and wastewater maintenance operations. The hose is the most common type of reinforced nonmetallic hose in general use. Many of the terms given have already been mentioned. The I.D., which designates the hose size, refers to the inside diameter throughout the length of the hose body, unless the hose has enlarged ends. The O.D. is the diameter of the outside wall of the hose.

As shown in Figure 8.17, the tube is the inner section (i.e., the core) of the hose, through which the fluid flows. Surrounding the tube is the reinforcement material, which provides resistance to pressure from the inside or outside. Notice that the hose shown in Figure 8.17 has two layers of reinforcement braid. (This braid is fashioned from high-strength synthetic cord.) The hose is said to be mandrel-braided, because a spindle or core (the mandrel) is inserted into the tube before the reinforcing materials are added. The mandrel provides a firm foundation over which the cords are evenly and tightly braided. The cover of the hose is an outer, protective covering. The hose in Figure 8.17 has a cover of tough, abrasion-resistant material.

Important Point: If the ends of an industrial hose are enlarged, as shown in Figure 8.18, the letters E.E. are used (meaning expanded or enlarged end). Some hoses have enlarged ends to fit a fixed end of piping tightly (e.g., an automobile engine).

The overall length is the true length of a straight piece of hose. The hose, which is not too flexible, is formed or molded in a curve (e.g., automobile hose used in heating systems; see Figure 8.19). As shown in Figure 8.19, the arm is the section of a curved hose that extends from the end of the hose to the nearest centerline intersection. The body is the middle section or sections of the curved hose. Figure 8.20 shows the bend radius (i.e., is the radius of the bend measured to the centerline) of the curved hose, and designated as the radius r. In a straight hose, bent on

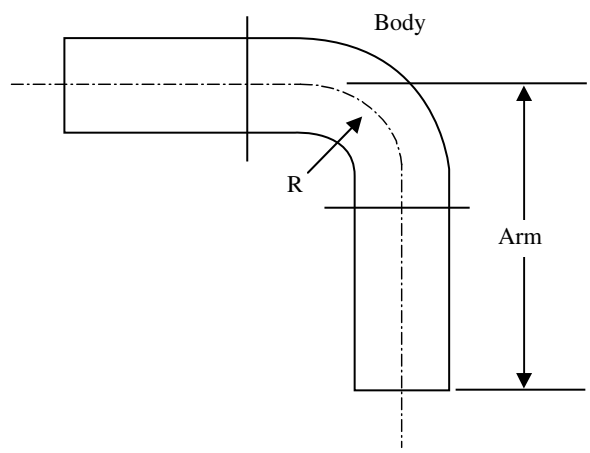

FIGURE 8.19 Bend radius. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

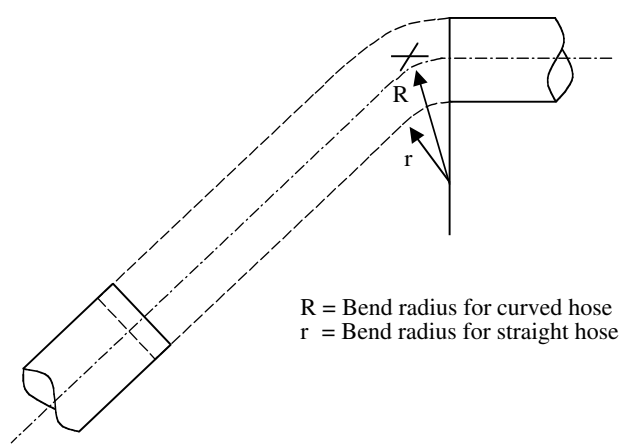

FIGURE 8.20 Bend radius measurement. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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the job, the radius of the bend is measured to the surface of the hose (i.e., radius r in Figure 8.20).

Important Point: Much of the nomenclature used above does not apply to non-metallic hose that is not reinforced. However, nonreinforced non-metallic hose is not very common in water and wastewater treatment plant operations.

8.6.2 Factors Governing Hose Selection

The amount of pressure that a hose will be required to convey is one of the important factors governing hose selection. Typically, pressure range falls in any of three general groups:

1. <250 psi (low pressure applications)
2. 250 to 3000 psi (medium pressure applications)
3. 3000 to 6000+ psi (high pressure applications)

Important Point: Note that some manufacturers have their own distinct hose pressure rating scheme; we cannot assume that a hose rated as low-pressure hose will automatically be useful at 100 or 200 psi. It may, in fact, be built for pressures not to exceed 50 psi, for example. Therefore, whenever we replace a particular hose, we must ensure that the same type of hose with the same pressure rating as the original hose is used. In high-pressure applications, this precaution is of particular importance.

In addition to the pressure rating of a hose, we must also consider, for some applications, the *vacuum rating* of a hose. Vacuum rating refers to suction hose applications, in which the pressure outside the hose is greater than the pressure inside the hose. It is important to know the degree of vacuum that can be created before a hose begins to collapse. A drinking straw, for example, collapses rather easily if too much vacuum is applied. Thus, it has a low vacuum rating. In contrast, the lower automobile radiator hose (also works under vacuum) has a relatively higher vacuum rating.

8.6.3 Standards, Codes, and Sizes

Just as they have for piping and tubing, authoritative standards organizations have devised standards and codes for hoses.

Standards and codes are safety measures designed to protect personnel and equipment. For example, specifications are provided for working pressures, sizes, and material requirements. The working pressure of a hose, for example, is typically limited to 1/4, or 25%, of the amount of pressure needed to burst the hose. For example, if we have a hose that has a maximum rated working pressure of 200 psi, it should not rupture until 800 psi has been reached, and possibly not even then. Thus, the use of hoses that meet specified standards or codes is quite evident.

8.6.3.1 Hose Size

The parameter typically used to designate hose size is its I.D. In regards to classification of a hose, ordinarily a dash numbering system is used. Current practice by most manufacturers is to use the dash system to identify both hose and fittings. In determining the size of a hose, we simply convert the size to 16ths. For example, a hose size of 1/2 in. (a hose with a 1/2-in. I.D.) is the same as 8/16 in. The numerator of the faction (the top number, or 8 in this case) is the dash size of the hose. In the same way, a 1½-in. size can be converted to 24/16 in. and so is identified as a -24 (pronounced dash 24) hose. By using the dash system, we can match a hose line to tubing or piping section and be sure the I.D. of both will be the same. This means that the non-turbulent flow of fluid will not be interrupted. Based on I.D., hoses range in size from 3/16 in. to as large as 24 in.

8.6.4 Hose Classifications

There are a number of ways in which a hose is classified. For example, hoses can be classified by type of service (hydraulic, pneumatic, corrosion-resistant), material, pressure, and type of construction. Hoses may also be classified by type. The three types include metallic, nonmetallic, and reinforced nonmetallic. Generally, terminology is the same for each type.

8.6.4.1 Nonmetallic Hoses

Relatively speaking, the use of hoses is not a recent development. Hoses, in fact, have been used for one application or another for hundreds of years. Approximately 100 years ago, after new developments in the processing of rubber, layering rubber around mandrels usually made hoses. Later, the mandrel was removed, leaving a flexible rubber hose. These flexible hoses tended to collapse easily. Even so, they were an improvement over the earlier types. Manufacturers later added layers of rubberized canvas. This improvement gave hoses more strength, and gave them the ability to handle higher pressures. Later, after the development of synthetic materials, manufacturers had more rugged and more corrosion-resistant rubber-type materials to work with. Today, neoprene, nitrile rubber, and butyl rubber are commonly used in hoses.

However, current manufacturing practice is not to make hoses from a single material. Instead, different materials form layers in the hose, reinforcing it in various ways for strength and resistance to pressure. Hoses manufactured today usually have a rubber-type inner tube or a synthetic (e.g., plastic) lining surrounded by a carcass

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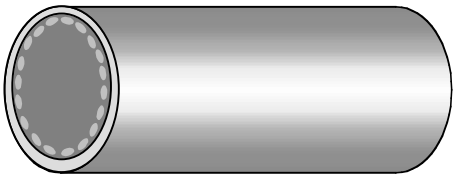

FIGURE 8.21 Vertical braided. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

(usually braided) and cover, as we saw in Figure 8.17. The type of carcass braiding used is determined by the requirements of the application.

To reinforce a hose, two types of braiding are used: vertical braiding and horizontal braiding. Vertical braiding strengthens the hose against pressure applied at right angles to the centerline of the hose. Horizontal braiding strengthens the hose along its length, giving it greater resistance to expansion and contraction.

8.6.4.1.1 Types of Nonmetallic Hoses

Descriptions of the types of nonmetallic hose follow, with references to their general applications.

8.6.4.1.1.1 Vertical-Braided Hoses

The vertical-braided hose has an inner tube of seamless rubber (see Figure 8.21). The reinforcing wrapping (carcass) around the tube is made of one or more layers of braided yarn. This type of hose is usually made in lengths of up to 100 ft with I.D.s of up to 1.5 in. Considered a small hose, it is used in low-pressure applications to carry fuel oil, acetylene gas, and oxygen for welding, and for watering lawns, gardens, and for other household uses. It is also used for spraying paint.

8.6.4.1.1.2 Horizontal-Braided Hoses

The horizontal-braided hose is mandrel built; it is used to make hose with an I.D. of up to 3 in. Used in high-pressure applications, the seamless rubber tube is reinforced by one or more layers of braided fibers or wire. This hose is used to carry propane and butane gas and steam, and is used for various hydraulic applications that require high working pressures.

8.6.4.1.1.3 Reinforced Horizontal Braided-Wire Hoses

In this type of hose, the carcasses around the seamless tube are made up of two or more layers of fiber braid with steel wire reinforcement between them. The I.D. may be up to 4 in. Mechanically very strong, this hose is used where there are high working pressures and strong suction (vacuum) forces, such as in chemical transfer and petroleum applications.

8.6.4.1.1.4 Wrapped Hoses

Made in diameters up to 24 in., the wrapped hose is primarily used for pressure service rather than suction. The hose is constructed of mandrels, and to close tolerances (see Figure 8.22). It also has a smooth bore that

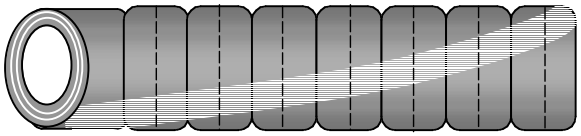

FIGURE 8.22 Wrapped hose. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

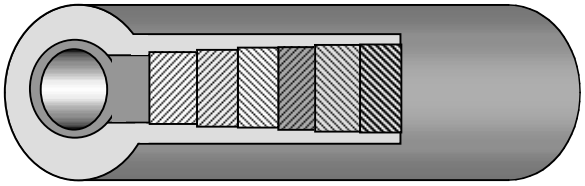

FIGURE 8.23 Wire-reinforced hose. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

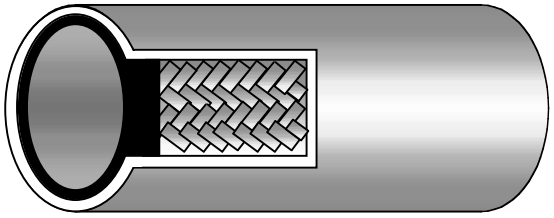

FIGURE 8.24 Wire-woven hose. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

encourages laminar flow and avoids turbulence. Several plies (layers) of woven cotton or synthetic fabric make up the reinforcement. Selected for their resistance to corrosive fluids, the tube is made from a number of synthetic rubbers. It is also used in sandblasting applications.

8.6.4.1.1.5 Wire-Reinforced Hoses

In this type of hose, wires wound in a spiral around the tube, or inside the carcass, in addition to a number of layers of wrapped fabrics, provide the reinforcement (see Figure 8.23). With I.D.s of 16 to 24 in. common, this type of hose is used in oil-suction and discharge situations that require special hose ends, maximum suction (without collapsing), special flexing characteristics (must be able to bend in a small radius without collapsing), or a combination of these three requirements.

8.6.4.1.1.6 Wire-Woven Hoses

The wire-woven hose (see Figure 8.24) has cords interwoven with wire running spirally around the tube, and is highly flexible, low in weight, and resistant to collapse even under suction conditions. This kind of hose is well suited for such negative pressure applications.

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8.6.4.1.1.7 Other Types of Nonmetallic Hoses

Hoses are also made of other nonmetallic materials, many of them nonreinforced. For example, materials like Teflon®, Dacron®, polyethylene, and nylon have been developed. Dacron remains flexible at very low temperatures, even as lows as –200+°C (up to –350°F), nearly the temperature of liquid nitrogen. Consequently, these hoses are used to carry liquefied gas in cryogenic applications.

Where corrosive fluids and fluids up to 230+°C (up to 450°F) are to be carried, Teflon is often used. Teflon can also be used at temperatures as low as –55°C (–65°F). Usually sheathed in a flexible, braided metal covering, Teflon hoses are well protected against abrasion; they also have added resistance to pressure.

Nylon hoses (small diameter) are commonly used as air hoses, supplying compressed air to small pneumatic tools. The large plastic hoses (up to 24 in.) we use to ventilate manholes are made of such neoprene-coated materials as nylon fabric, glass fabric, and cotton duck. The cotton duck variety is for light-duty applications. The glass fabric type is used with portable heaters and for other applications involving hot air and fumes.

Various hoses made from natural latex, silicone rubber, and pure gum are available. The pure gum hose will safely carry acids, chemicals, and gases. Small hoses of natural latex, which can be sterilized, are used in hospitals; with pharmaceuticals, blood, and intravenous solutions; and in food-handling operations and laboratories. Silicone rubber hose is used in situations where extreme temperatures and chemical reactions are possible. It is also used as for aircraft starters, to which it provides compressed air in very large volumes. Silicone rubber hose works successfully over a temperature range from –57 to 232°C (–70 to 450°F).

8.6.4.2 Metallic Hoses

The construction of a braided, flexible all-metal hose includes a tube of corrugated bronze. The tube is covered with the woven metallic braid to protect against abrasion, and to provide increased resistance to pressure. Metal hose is also available in steel, aluminum, Monel®, stainless steel, and other corrosion-resistant metals in diameters up to 3 in. and in lengths of 24 in.

In addition to providing protection against abrasion and resistance to pressure, the flexible metal hose also dampens vibration. For example, a plant air compressor produces a considerable amount of vibration. The flexible hoses from such machines increase mobility for portable equipment and dampen the vibration. Other considerations such as constant bending at high temperatures and pressures are extremely detrimental on most other types of hoses.

Other common uses for metallic hoses include serving as steam lines, lubricating lines, gas and oil lines, and exhaust hose for diesel engines. The corrugated type, for example, is used for high-temperature, high-pressure leakproof service. Another type of construction is the interlocked flexible metal hose, used mainly for low-pressure applications. The standard shop oil can use a flexible hose for the flexible spout. Other metal hoses, with a liner of flexible, corrosion-resistant material, are available in diameters of up to 24 in.

Another type of metallic hose is used in ductwork. These are usually made of aluminum, galvanized steel, and stainless steel. They are used to protect against corrosive fumes, as well as gases at extreme hot or cold temperatures. They usually do not burn because they are also fire resistant.

8.6.5 Hose Couplings

The methods of connecting or coupling hoses vary. Hose couplings may be either permanent or reusable. They can also be manufactured for the obvious advantage of quick-connect or quick-disconnect. Probably the best example of the need for quick-connect is fire hose — quick-disconnect couplings permit rapid connection between separate lengths of hose, and between hose ends and hydrants or nozzles. Another good example of where the quick-connect, quick-disconnect feature is user-friendly is in plant or mobile compressed air systems — a single line may have a number of uses. Changes involve disconnecting one section and connecting another. In plant shops, for example, compressed air from a single source is used to power pneumatic tools, cleaning units, paint sprayers, and so on. Each unit has a hose that is equipped for rapid connecting and disconnecting at the fixed airline.

Important Point: Caution: Before connections are broken, unless quick-acting, self-closing connectors are used, pressure must be released first.

For general low-pressure applications, a coupling like that shown in Figure 8.25 is used. To place this coupling on the hose by hand, first cut hose to proper length, and then oil inside of hose and outside of the coupling stem. Force the hose over the stem into the protective cap until it seats against bottom of the cap. No brazing is involved, and the coupling can be used repeatedly. After the coupling has been inserted in the hose, a yoke is placed over it in such a way that its arms are positioned along opposite sides of the hose behind the fitting. The arms are then tightly strapped or banded.

Important Point: Caution: Where the pressure demands are greater, such a coupling can be blown out of the tube. Hose couplings designed to meet high-pressure applications must be used.

A variation of this type uses a clamp that is put over the inner end of the fitting and is then tightly bolted, thus

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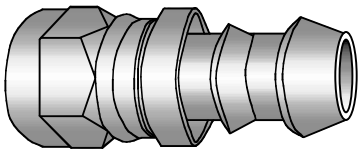

FIGURE 8.25 Low-pressure hose coupling. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

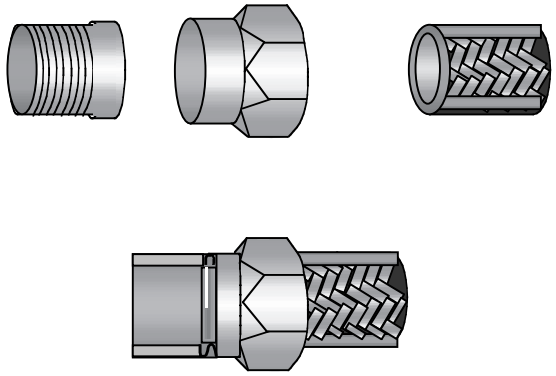

FIGURE 8.26 Coupling installation for all-metal hose. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

holding the hose firmly. In other cases, a plain clamp is used. Each size clamp is designed for a hose of a specified size (diameter). The clamp slides snugly over the hose, and is then crimped tight by means of a special hand tool or air-powered tool.

Couplings for all-metal hoses, described earlier, involve two brazing operations, as shown in Figure 8.26. The sleeve is slipped over the hose end and brazed to it, and then the nipple is brazed to the sleeve.

Important Point: For large hoses of rugged wall construction, it is not possible to insert push-on fittings by hand. Special bench tools are required.

Quick-connect, quick-disconnect hose couplings provide flexibility in many plant process lines where a number of different fluids or dry chemicals from a single source are either to be blended or routed to different vats or other containers. Quick-connect couplings can be used to pump out excavations, manholes, and so forth. They would not be used where highly corrosive materials are involved.

8.6.6 Hose Maintenance

All types of equipment and machinery require proper care and maintenance, including hoses. Depending on the hose type and its application, some require more frequent checking than others. The maintenance procedures required for most hoses are typical, and are outlined here as an example.

To maintain a hose, we should:

1. Examine for cracks in the cover caused by weather, heat, oil, or usage.
2. Look for a restricted bore because of tube-swelling or foreign objects.
3. Look for cover blisters, which permit material pockets to form between carcass and cover.
4. Look for leaking materials, which is usually caused by improper couplings or faulty fastenings of couplings.
5. Look for corrosion damage to couplings.
6. Look for kinked or otherwise damaged hose.

Important Point: Caution: Because any of the faults listed above can result in a dangerous hose failure, regular inspection is necessary. At the first sign of weakness or failure, replace the hose. System pressure and temperature gauges should be checked regularly. Do not allow the system to operate above design conditions — especially when hose is a component of the system.

8.7 PIPE AND TUBE FITTINGS

The term piping refers to the overall network of pipes or tubing, fittings, flanges, valves, and other components that comprise a conduit system used to convey fluids. Whether a piping system is used to simply convey fluids from one point to another or to process and condition the fluid, piping components serve an important role in the composition and operation of the system. A system used solely to convey fluids may consist of relatively few components, such as valves and fittings, whereas a complex chemical processing system may consist of a variety of components used to measure, control, condition, and convey the fluids. In this section, the characteristics and functions of various piping and tubing fittings are described.[36]

8.7.1 Fittings

The primary function of fittings is to connect sections of piping and tubing and to change direction of flow. Whether used in piping or tubing, fittings are similar in shape and type, even though pipefittings are usually heavier than tubing fittings. Several methods can be used to connect fittings to piping and tubing systems. However, most tubing is threadless because it does not have the wall thickness needed to carry threads. Most pipes, on the other hand, because they have heavier walls, are threaded.

In regard to changing direction of flow, the simplest way would be simply to bend the conduit; this is not always practical or possible. When piping is bent, it is usually accomplished by the manufacturer in the production process (in larger shops equipped with their own pipe-bending

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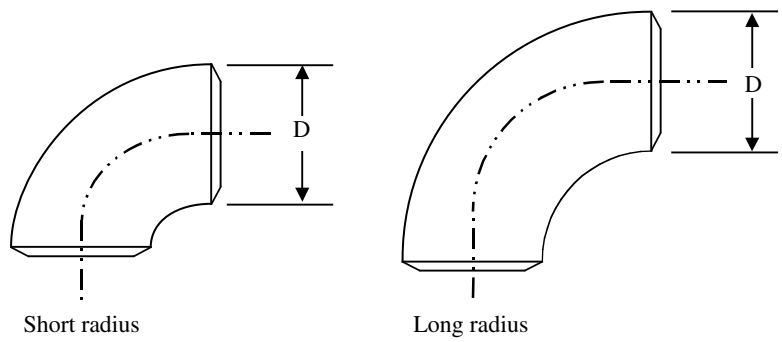

FIGURE 8.27 Short and long radius elbows. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

machines), but not by the maintenance operator on the job. Tube bending, on the other hand, is a common practice. Generally, a tubing line requires fewer fittings than a pipeline; however, in actual practice many tube fittings are used.

Important Point: Recall that improperly made bends can restrict fluid flow by changing the shape of the pipe and weakening the pipe wall.

Fittings are basically made from the same materials (and in the same broad ranges of sizes) as piping and tubing, including bronze, steel, cast iron, glass, and plastic.

Various established standards are in place to ensure that fittings are made from the proper materials and are able to withstand the pressures required; they are also made to specific tolerances, so that they will properly match the piping or tubing that they join. A fitting stamped 200 lb, for example, is suitable (and safe) for use up to 200 psi.

8.7.2 Functions of Fittings

Fittings in piping and tubing systems have five main functions:

1. Changing the direction of flow
2. Providing branch connections
3. Changing the sizes of lines
4. Closing lines
5. Connecting lines

8.7.2.1 Changing the Direction of Flow

Usually a 45° or 90° elbow (or ell) fitting is used to change the direction of flow. Elbows are among the most commonly used fittings in piping, and are occasionally used in tubing systems.

Two types of 90° elbows are shown in Figure 8.27. From the figure, it is apparent that the *long-radius* fitting (the most preferred elbow) has the more gradual curve of the two. This type of elbow is used in applications where the rate of flow is critical, and space presents no problem. Flow loss caused by turbulence is minimized by the gradual curve.

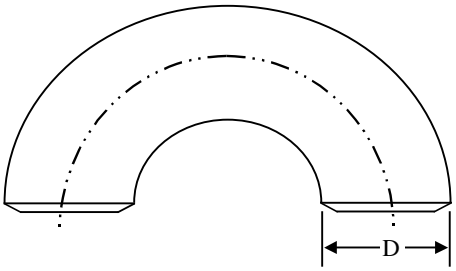

FIGURE 8.28 Long-radius return bend. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

The short-radius elbow (see Figure 8.27) should not be used in a system made up of long lines and has many changes in direction. Because of the greater frictional loss in the short-radius elbow, heavier and more expensive pumping equipment may be required.

Figure 8.28 shows a return bend fitting that carries fluid through a 180° (hairpin) turn. This type of fitting is used for piping in heat exchangers and heater coils. Note that tubing, which can be bent into this form, does not require any fittings in this kind of application.

8.7.2.2 Providing Branch Connections

Because they are often more than single lines running from one point to another point, piping and tubing systems usually have a number of intersections. In fact, many complex piping and tubing systems resemble the layout of a town or city.

8.7.2.3 Changing the Sizes of Lines

For certain applications, it is important to reduce the volume of fluid flow or to increase flow pressure in a piping or tubing system. To accomplish this, a reducer (which reduces a line to a smaller pipe size) is commonly used.

Important Point: Reducing is also sometimes accomplished by means of a bushing inserted into the fitting.

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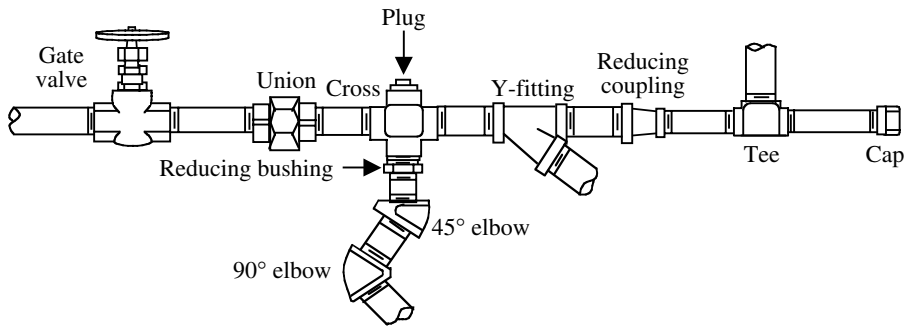

FIGURE 8.29 Diagram of a hypothetical shortened piping system. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

8.7.2.4 Sealing Lines

Pipe caps are used to seal or close off (similar to corking a bottle) the end of a pipe or tube. Usually, caps are used in a part of the system that has been dismantled.

To seal off openings in fittings, *plugs* are used. Plugs also provide a means of access into the piping or tubing system, in case the line becomes clogged.

8.7.2.5 Connecting Lines

To connect two lengths of piping or tubing together, a coupling or union is used. A coupling is simply a threaded sleeve. A union is three-piece device that includes a threaded end, an internally threaded bottom end, and a ring. A union does not change the direction of flow, close off the pipe, or provide for a branch line. Unions make it easy to connect or disconnect pipes without disturbing the position of the pipes.

Figure 8.29 is a diagram of a shortened piping system that illustrates how some fittings are used in a piping system. (Note: Figure 8.29 is only for illustrative purposes; it is unlikely that such a system with so many fittings would actually be used.)

8.7.3 Types of Connections

Pipe connections may be screwed, flanged, or welded. Each method is widely used, and each has its own advantages and disadvantages.

8.7.3.1 Screwed Fittings

Screwed fittings are joined to the pipe by means of threads. The main advantage of using threaded pipefittings is that they can be easily replaced. The actual threading of a section of replacement pipe can be accomplished on the job. The threading process itself, which cuts right into the pipe material, may weaken the pipe in the joint area.

The weakest link in a piping system is the connection point. Because threaded joints can be potential problem areas, especially where higher pressures are involved, the threads must be properly cut to ensure the weakest link is not further compromised.

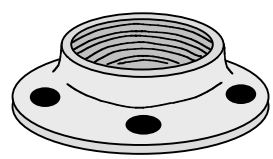

FIGURE 8.30 Flanged fitting. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

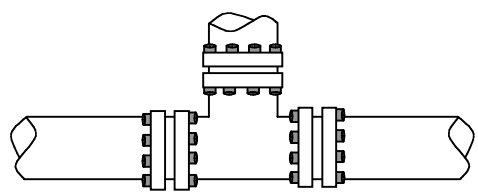

FIGURE 8.31 Flanged joint. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Typically, the method used to ensure a good seal in a threaded fitting is to coat the threads with a paste dope. Another method is to wind the threads with Teflon® tape.

8.7.3.2 Flanged Connections

Figure 8.30 shows a flanged fitting. Flanged fittings are forged or cast iron pipe. The flange is a rim at the end of the fitting, which mates with another section. Pipe sections are also made with flanged ends.

Flanges are joined either by being bolted or welded together. The flange faces may be ground and lapped to provide smooth, flat mating surfaces. Obviously, a tight joint must be provided to prevent leakage of fluid and pressure.

Figure 8.31 shows a typical example of a flanged joint. The mating parts are bolted together with a gasket inserted between their faces to ensure a tight seal. The procedure requires proper alignment of clean parts and tightening of bolts.

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Important Point: Some flanges have raised faces and others have plain faces. Like faces must be matched; a flange with a raised face should never be joined to one with a plain face.

8.7.3.3 Connections

Currently, because of improvements in piping technology and welding techniques and equipment, the practice of using welded joints is increasing. When properly welded, a piping system forms a continuous system, combining piping, valves, flanges, and other fittings. Along with providing a long leak-proof and maintenance-free life, the smooth joints simplify insulation and take up less room.

8.7.4 Tubing Fittings and Connections

Tubing is connected by brazed or welded flange fittings, compression fittings, and flare fittings.

The welded flange connection is a reliable means of connecting tubing components. The flange welded to the tube end fits against the end of the fitting. The locknut of the flange is then tightened securely onto the fitting.

The compression fitting connection uses a ferrule that pinches the tube as the locknut is tightened on the body of the fitting.

The flare fitting connection uses tubing flared on one end of the tubing that matches the angle of the fitting. The tube's flared end is butted against the fitting, and a locknut is screwed tightly onto the fitting, sealing the tube connection properly.

Other fittings used for flanged connections include expansion joints and vibration dampeners.

Expansion joints function to compensate for slight changes in the length of pipe by allowing joined sections of rigid pipe to expand and contract with changes in temperature. They also allow pipe motion, either along the length of the pipe or to the side, as the pipe shifts around slightly after installation. Finally, expansion joints also help dampen vibration and noise carried along the pipe from distant equipment (e.g., pumps).

One type of expansion joint has a leak-proof tube that extends through the bore and forms the outside surfaces of the flanges. Natural or synthetic rubber compounds are normally used, depending on the application.

Other types of expansion joints include metal corrugated types, slip-joint types, and spiral-wound types. In addition, high-temperature lines are usually made up with a large bend or loop to allow for expansion.

Vibration dampeners absorb vibrations that, unless reduced, could shorten the life of the pipe and the service life of the operating equipment. They also eliminate line humming and hammering (water hammer) carried by the pipes.

8.8 VALVES

Any water or wastewater operation will have many valves that require attention. Simply as a matter of routine, a maintenance operator must be able to identify and locate different valves in order to inspect them, adjust them, and repair or replace them. For this reason, the operator should be familiar with all valves, especially those that are vital parts of a piping system.

A valve is defined as any device by which the flow of fluid may be started, stopped, or regulated by a movable part that opens or obstructs passage. As applied in fluid power systems, valves are used for controlling the flow, the pressure, and the direction of the fluid flow through a piping system. The fluid may be a liquid, a gas, or some loose material in bulk (like a biosolids slurry). Designs of valves vary, but all valves have two features in common: a passageway through which fluid can flow and some kind of movable (usually machined) part that opens and closes the passageway.[37]

Important Point: It is all but impossible to operate a practical fluid power system without some means of controlling the volume and pressure of the fluid and directing the flow of fluid to the operating units. This is accomplished by the incorporation of different types of valves.

Whatever type of valve is used in a system, it must be accurate in the control of fluid flow and pressure and the sequence of operation. Leakage between the valve element and the valve seat is reduced to a negligible quantity by precision-machined surfaces, resulting in carefully controlled clearances. This is one of the very important reasons for minimizing contamination in fluid power systems. Contamination causes valves to stick; plugs small orifices; and causes abrasions of the valve seating surfaces, which result in leakage between the valve element and valve seat when the valve is in the closed position. Any of these can result in inefficient operation or complete stoppage of the equipment. Valves may be controlled manually, electrically, pneumatically, mechanically, hydraulically, or by combinations of two or more of these methods. Factors that determine the method of control include the purpose of the valve, the design and purpose of the system, the location of the valve within the system, and the availability of the source of power.

Valves are made from bronze, cast iron, steel, Monel®, stainless steel, and other metals. They are also made from plastic and glass (see Table 8.1). Special valve trim is used where seating and sealing materials are different from the basic material of construction (see Table 8.2). (Note: Valve trim usually means those internal parts of a valve controlling the flow and in physical contact with the line fluid.) Valves are made in a full range of sizes, which match pipe and tubing sizes. Actual valve size is based upon the

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TABLE 8.1
Valves: Materials of Construction

Cast iron	Grey cast iron; also referred to as flake graphite iron
Ductile iron	May be malleable iron or spheroidal graphite (nodular) cast iron
Carbon steel	May be as steel forgings or steel castings, according to the method of manufacture; carbon steel valves may also be manufactured by fabrication using wrought steels
Stainless steel	May also be in the form of forgings, castings, or wrought steels for fabrication
Copper alloy	May be gunmetal, bronze, or brass; aluminum bronze may also be used.
High Duty alloys	Are usually those nickel or nickel molybdenum alloys manufactured under various trade names
Other metals	Are those pure metals having extreme corrosion resistance such as titanium or aluminum
Nonmetals	Are typically the plastics materials such as PVC or polypropylene

Source: From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.

TABLE 8.2
Valve Trim

Metal seating	Is commonly used in gate and globe valves, and in the latter particularly for control applications where seatings may additionally be coated with hard metal
Soft seating	Is commonly used in ball, butterfly, and diaphragm valves; seatings may be made from a wide variety of elastomers and polymers, including fluorocarbons.
Lined	Valves are usually made in cast iron with an internal lining of elastomer of polymer material; inorganic materials such as glass, together with metals such as titanium are so used for lining; lining thickness will depend upon design and the type of material used; in many cases, the valve lining will also form the seating trim

Source: From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.

TABLE 8.3
Valve End Connections

Flanged	Valves will normally be supplied with flanges confirming to either BS4505 (equivalent to DIN) or BS 1560 (equivalent to ANSI) according to specification; manufacturers may be able to supply valves with flanges to other standards
Threaded	Valves will normally be supplied with threads to BS21 (ISO/7) parallel or taper
Other	End connections include butt or socket weld ends and wafer valves designed to fit between pipe flanges.

Source: From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.

internationally agreed definition of nominal size. Nominal size (DN) is a numerical designation of size that is common to all components in a piping system other than components designated by outside diameters. It is a convenient number for reference purposes and is only loosely related to manufacturing dimensions. Valves are made for service at the same pressures and temperatures that piping and tubing is subject to.

Valve pressures are based upon the internationally agreed definition of nominal pressure. Nominal pressure (PN) is a pressure that is conventionally accepted or used for reference purposes. All equipment of the same DN designated by the same PN number must have the same mating dimensions appropriate to the type of end connections. The permissible working pressure depends upon materials, design, and working temperature; it should be selected from the (relevant), pressure/temperature tables. The pressure rating of many valves is designated under the ANSI class system. The equivalent class rating to PN ratings is based upon international agreement.

Usually, valve end connections are classified as flanged, threaded, or other (see Table 8.3).

Valves are also covered by various codes and standards, as are the other components of piping and tubing systems.

Many valve manufacturers offer valves with special features. Table 8.4 lists a few of these special features. This is not an exhaustive list and for more details of other features, the manufacturer should be consulted.

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TABLE 8.4
Valve Special Features

High temperature	Valves are those usually able to operate continuously on services above 250°C
Cryogenic	Valves are those that will operate continuously on services in the range –50 to 196°C
Bellows sealed	Valves are glandless designs having a metal bellows for stem sealing
Actuated	Valves may be operated by a gearbox, pneumatic, or hydraulic cylinder (including diaphragm actuator), or electric motor and gearbox
Fire tested design	Refers to a valve that has passed a fire test procedure specified in an appropriate inspection standard

Source: From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.

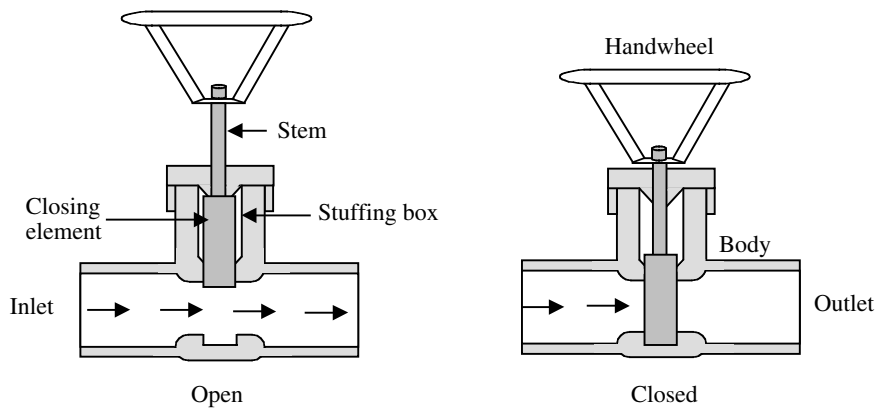

FIGURE 8.32 Basic valve operation. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

The different types of valves used in fluid power systems, their classifications, and their applications are discussed in this chapter.

8.8.1 Valve Construction

Figure 8.32 shows the basic construction and principle of operation of a common valve type. Fluid flows into the valve through the inlet. The fluid flows through passages in the body and past the opened element that closes the valve. It then flows out of the valve through the outlet or discharge.

If the closing element is in the closed position, the passageway is blocked. Fluid flow is stopped at that point. The closing element keeps the flow blocked until the valve is opened again. Some valves are opened automatically, and manually operated hand wheels control others. Other valves, such as check valves, operate in response to pressure or the direction of flow.

A seal is used to prevent leakage whenever the closing element is positioned in the closed position. In Figure 8.34, the seal consists of a *stuffing box* fitted with packing. The closing element fits against the *seat* in the valve body to keep the valve tightly closed.

8.8.2 Types of Valves

The types of valves covered in this text include the following:

1. Ball valves
2. Gate valves
3. Globe valves
4. Needle valves
5. Butterfly valves
6. Plug valves
7. Check valves
8. Quick-opening valves
9. Diaphragm valves
10. Regulating valves
11. Relief valves
12. Reducing valves

Each of these valves is designed to perform either control of the flow, the pressure, and the direction of fluid flow or for some other special application. With a few exceptions, these valves take their names from the type of internal element that controls the passageway. The exceptions are the check valve, quick-opening valve, regulating valve, relief valve, and reducing valves.

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8.8.2.1 Ball Valves

Ball valves, as the name implies, are stop valves that use a ball to stop or start fluid flow. The ball performs the same function as the disk in other valves. As the valve handle is turned to open the valve, the ball rotates to a point where part or all of the hole through the ball is in line with the valve body inlet and outlet, allowing fluid to flow through the valve. When the ball is rotated so the hole is perpendicular to the flow openings of the valve body, the flow of fluid stops.

Most ball valves are the quick-acting type. They require only a 90-degree turn to either completely open or close the valve. However, many are operated by planetary gears. This type of gearing allows the use of a relatively small hand wheel and operating force to operate a large valve. The gearing increases the operating time for the valve. Some ball valves also contain a swing check located within the ball to give the valve a check valve feature.

The two main advantages of using ball valves are: (1) the fluid can flow through it in either direction, as desired; and (2) when closed, pressure in the line helps to keep it closed.

8.8.2.2 Gate Valves

Gate valves are used when a straight-line flow of fluid and minimum flow restriction are needed; they are the most common type of valve found in a water distribution system. Gate valves are so named because the part that either stops or allows flow through the valve acts somewhat like a gate. The gate is usually wedge-shaped. When the valve is wide open, the gate is fully drawn up into the valve bonnet. This leaves an opening for flow through the valve the same size as the pipe in which the valve is installed. For these reasons, the pressure loss (pressure drop) through these types of valves is about equal to the loss in a piece of pipe of the same length. Gate valves are not suitable for throttling (means to control the flow as desired, by means of intermediate steps between fully open and fully closed) purposes. The control of flow is difficult because of the valve's design, and the flow of fluid slapping against a partially open gate can cause extensive damage to the valve.

Important Point: Gate vales are well suited to service on equipment in distant locations where they may remain in the open or closed position for a long time. Generally, gate valves are not installed where they will need to be operated frequently because they require too much time to operate from fully open to closed.[38]

8.8.2.3 Globe Valves

Probably the most common valve type in existence, the globe valve principle is commonly used for water faucets and other household plumbing. As illustrated in Figure 8.33, the valves have a circular disk — the globe — that presses against the valve seat to close the valve. The disk is the part of the globe valve that controls flow. The disk is attached to the valve stem. As shown in Figure 8.33, fluid flow through a globe valve is at right angles to the direction of flow in the conduits. Globe valves seat very tightly, and can be adjusted with fewer turns of the wheel than gate valves; they are preferred for applications that call for frequent opening and closing. On the other hand, globe valves create high head loss when fully open; they are not suited in systems where head loss is critical.

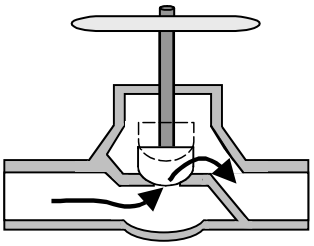

FIGURE 8.33 Globe valve. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Important Point: The globe valve should never be jammed in the open position. After a valve is fully opened, the hand wheel should be turned toward the closed position approximately one-half turn. Unless this is done, the valve is likely to seize in the open position, making it difficult, if not impossible, to close the valve. Another reason for not leaving globe valves in the fully open position is that it is sometimes difficult to determine if the valve is open or closed.[39]

8.8.2.4 Needle Valves

Although similar in design and operation to the globe valve (a variation of globe valves), the needle valve has a closing element in the shape of a long tapered point that is at the end of the valve stem. Figure 8.34 shows a cross-sectional view of a needle valve; the long taper of the valve closing element permits a much smaller seating

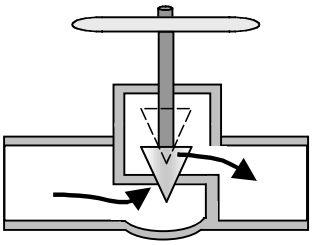

FIGURE 8.34 Common needle valve. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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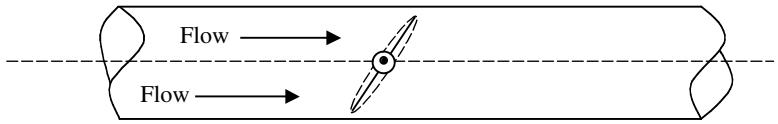

FIGURE 8.35 Cross-section of butterfly valve. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

surface area than the globe valve's; accordingly, the needle valve is more suitable as a throttle valve. In fact, needle valves are used for very accurate throttling.

8.8.2.5 Butterfly Valves

Figure 8.35 shows a cross-sectional view of a butterfly valve. The valve consists of a body in which a disk (butterfly) rotates on a shaft to open or close the valve. Butterfly valves may be flanged or wafer design, the latter intended for fitting directly between pipeline flanges. In the full open position, the disk is parallel to the axis of the pipe and the flow of fluid. In the closed position, the disk seals against a rubber gasket-type material bonded either on the valve seat of the body or on the edge of the disk. Because the disk of a butterfly valve stays in the fluid path in the open position, the valve creates more turbulence (higher resistance to flow, equaling a higher pressure loss) than a gate valve.

On the other hand, butterfly valves are compact. They can also be used to control flow in either direction. This feature is useful in water treatment plants that periodically backwash to clean filter systems.

8.8.2.6 Plug Valves

A plug valve (also known as a cock, or petcock) is similar to a ball valve. Plug valve properties include:

1. High capacity operation, quarter-turn operation
2. A cylindrical or conical plug used as the closing member
3. Directional
4. Moderate vacuum service
5. Flow throttling with interim positioning
6. Simple construction; o-ring seal
7. Not necessarily full on and off
8. Easily adapted to automatic control
9. Safely handles gases and liquids

8.8.2.7 Check Valves

Check valves are usually self-acting and designed to allow the flow of fluid in one direction only. They are commonly used at the discharge of a pump to prevent backflow when the power is turned off. When the direction of flow is moving in the proper direction, the valve remains open. When the direction of flow reverses, the valve closes automatically from the fluid pressure against it.

There are several types of check valves used in water and wastewater operations, including

1. Slanting disk check valves
2. Cushioned swing check valves
3. Rubber flapper swing check valves
4. Double door check valves
5. Ball check valves
6. Foot valves
7. Backflow prevention devices

In each case, pressure from the flow in the proper direction pushes the valve element to an open position. Flow in the reverse direction pushes the valve element to a closed position.

Important Point: Check valves are also commonly referred to as nonreturn or reflux valves.

8.8.2.8 Quick-Opening Valves

Quick-opening valves are nothing more than adaptations of some of the valves already described. Modified to provide a quick on and off action, they use a lever device in place of the usual threaded stem and control handle to operate the valve. This type of valve is commonly used in water and wastewater operations where deluge showers and emergency eyewash stations are installed in work areas where chemicals are loaded and transferred, and chemical systems are maintained. They also control the air supply for some emergency alarm horns, around chlorine storage areas, for example. Moreover, they are usually used to cut off the flow of gas to a main or to individual outlets.

8.8.2.9 Diaphragm Valves

Diaphragm valves are glandless valves that use a flexible elastomeric diaphragm (a flexible disk) as the closing member and also affect an external seal. They are well suited to service in applications where tight, accurate closure is important. The tight seal is effective whether the fluid is a gas or a liquid. This tight closure feature makes these valves useful in vacuum applications. Diaphragm valves operate similar to globe valves and are usually multiturn in operation; they are available as weir type and full bore. A common application of diaphragm valves in

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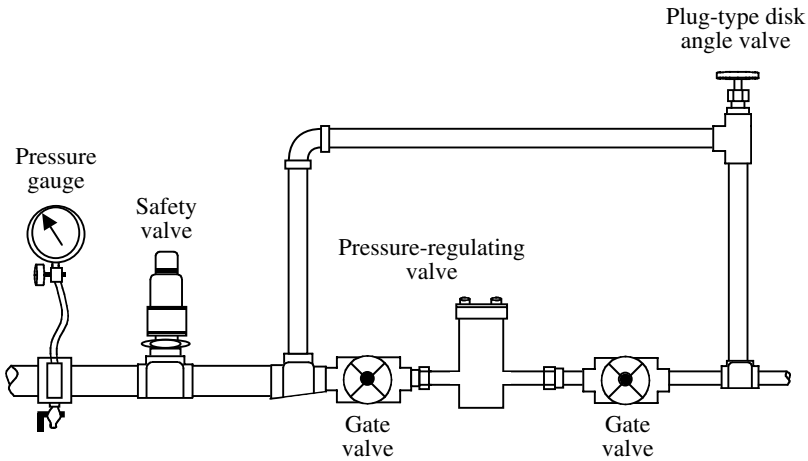

FIGURE 8.36 Pressure-regulating valve system. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

water and wastewater operations is to control fluid to an elevated tank.

8.8.2.10 Regulating Valves

As their name implies, regulating valves regulate either pressure or temperature in a fluid line, keeping them very close to a preset level. If the demands and conditions of a fluid line remained steady at all times, no regulator valve would be needed. In the real world, ideal conditions do not occur.

Pressure-regulating valves regulate fluid pressure levels to meet flow demand variations. Flow variations vary with the number of pieces of equipment in operation, and the change in demand as pumps and other machines operate. In such fluid line systems, demands are constantly changing. Probably the best example of this situation is seen in the operation of the plant's low-pressure air supply system. For shop use, no more than 30 psi air is usually required (depending on required usage, of course). This air is supplied by the plant's air compressor, which normally operates long enough to fill an accumulator with pressurized air at a set pressure level. When shop air is required, for whatever reason, compressed air is drawn from the connection point in the shop. The shop connection point is usually connected via a pressure reducer (sets the pressure at the desired usage level) that is fed from the accumulator where the compressed air is stored. If the user draws a large enough quantity of compressed air from the system (from the accumulator), a sensing device within the accumulator will send a signal to the air compressor to start, producing compressed air to recharge the accumulator.

As well as providing service in airlines, pressure-regulating valves are also used in liquid lines. The operating principle is much the same for both types of service. Simply, the valve is set to monitor the line, and to make needed adjustments in response to a signal from a sensing device.

Temperature-regulating valves (also referred to as thermostatic control valves) are closely related to pressure-regulating valves (see Figure 8.36). Their purpose is to monitor the temperature in a line or process solution tank, and to regulate it, raising or lowering the temperature as required.

In water and wastewater operations, probably the most familiar application where temperature-regulating valves (see Figure 8.37) are used is in heat exchangers. A heat exchanger-type water system utilizes a water-to-coolant heat exchanger for heat dissipation. This is an efficient and effective method to dispose of unwanted heat. Heat exchangers are equipped with temperature regulating valves that automatically modulate the shop process water, limiting usage to just what is required to achieve the desired coolant temperature.

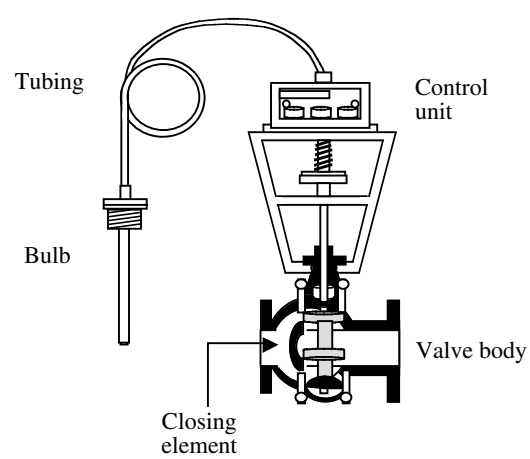

FIGURE 8.37 Temperature-regulating valve assembly. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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8.8.2.11 Relief Valves

Some fluid power systems, even when operating normally, may temporarily develop excessive pressure. For example, whenever an unusually strong work resistance is encountered, dangerously high pressure may develop. Relief valves are used to control this excess pressure. Such valves are automatic valves; they start to open at a preset pressure, but require a 20% overpressure to open wide. As the pressure increases, the valve continues to open further until it has reached its maximum travel. As the pressure drops, it starts to close, and finally shuts off at about the set pressure.

Main system relief valves are generally installed between the pump or pressure source and the first system isolation valve. The valve must be large enough to allow the full output of the hydraulic pump to be delivered back to the reservoir.

Important Point: Relief valves do not maintain flow or pressure at a given amount, but prevent pressure from rising above a specific level when the system is temporarily overloaded.

8.8.2.12 Reducing Valves

Pressure-reducing valves provide a steady pressure into a system that operates at a lower pressure than the supply system. In practice, they are very much like pressure-regulating valves. A pressure-reducing valve reduces pressure by throttling the fluid flow. A reducing valve can normally be set for any desired downstream pressure within the design limits of the valve. Once the valve is set, the reduced pressure will be maintained regardless of changes in supply pressure (as long as the supply pressure is at least as high as the reduced pressure desired) and regardless of the system load, providing the load does not exceed the design capacity of the reducer.

8.8.3 Valve Operators

In many modern water and wastewater operations, devices called operators or actuators mechanically operate many valves. These devices — pneumatic, hydraulic, and magnetic operators — may be operated by air, electricity, or fluid.

8.8.3.1 Pneumatic and Hydraulic Valve Operators

Pneumatic and hydraulic valve operators are much the same in appearance and work in much the same way. Hydraulic cylinders using either plant water pressure or hydraulic fluid frequently operate valves in treatment plants and pumping stations.[40] In a typical pneumatic ball-valve actuator, the cylinder assembly is attached to the ball-valve stem close to the pipe. A piston inside the cylinder can move in either direction. The piston rod is linked to the valve stem, opening or closing the valve, depending on the direction in which the piston is traveling. As a fail-safe feature, some of these valves are spring-loaded. In case of hydraulic or air pressure failure, the valve operator returns the valve to the safe position.

Note: According to Casada, valve operators and positioners usually require more maintenance than the valves themselves.[41]

8.8.3.2 Magnetic Valve Operators

Magnetic valve operators use electric solenoids. A solenoid is a coil of magnetic wire, roughly in the shape of a doughnut. When a bar of iron is inserted as a plunger mechanism inside an energized coil, it moves along the coil because of the magnetic field that is created. If the plunger (the iron bar) is fitted with a spring, it returns to its starting point when the electric current is turned off.

Solenoids are used as operators for many different types of valves used in water and wastewater operations. For example, in a direct-operating valve, the solenoid plunger is used in place of a valve stem and hand wheel. The plunger is connected directly to the disk of a globe valve. As the solenoid coil is energized or deenergized, the plunger rises or falls, operating or closing the valve.

8.8.4 Valve Maintenance

As with any other mechanical device, effective valve maintenance begins with its correct operation. As an example of incorrect operation, consider the standard household water faucet. As the faucet washers age, they harden and deteriorate. The valve becomes more difficult to operate properly, and eventually, the valve begins to leak. A common practice is simply to apply as much force as possible to the faucet handle. Unfortunately, this damages the valve stem and the body of the valve body.

Good maintenance includes preventive maintenance, which, in turn, includes inspection of valves, correct lubrication of all moving parts, and the replacement of seals or stem packing.

8.9 PIPING SYSTEM: PROTECTIVE DEVICES

Piping systems must be protected from the harmful effects of undesirable impurities (solid particles) entering the fluid stream. Because of the considerable variety of materials carried by piping systems, there is an equal range of choices in protective devices. Such protective devices include strainers, filters, and traps.

In this section, we describe the design and function of strainers, filters, and traps. The major maintenance considerations of these protective devices also are explained.

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8.9.1 Applications

Filters, strainers, and traps are normally thought of in terms of specific components used in specific systems. However, it is important to keep in mind that the basic principles apply in many systems. While the examples used in this chapter include applications found in water/wastewater treatment, collection, and distribution systems, the applications are also found in almost every plant — hot and cold water lines, lubricating lines, pneumatic and hydraulic lines, and steam lines.

In regards to steam lines, it is important to point out that in our discussion of traps, their primary application is in steam systems where they remove unwanted air and condensate from lines.

Important Point: A very large percentage (estimated to be >70%) of all plant facilities in the U.S. make use of steam in some applications.

Other system applications of piping protective devices include conveyance of hot and chilled water for heating and air conditioning, and lines that convey fluids for various processes. Any foreign contamination in any of these lines can cause potential trouble. Piping systems can become clogged, thereby causing greatly increased friction and lower line pressure. Foreign contaminants (dirt and other particles) can also damage valves, seals, and pumping components.

Important Point: Foreign particles in a high-pressure line can damage a valve by clogging the valve so that it cannot close tightly. In addition, foreign particles may wear away the closely machined valve parts.

8.9.2 Strainers[42]

Strainers, usually wire mesh screens, are used in piping systems to protect equipment sensitive to contamination that may be carried by the fluid. Strainers can be used in pipelines conveying air, gas, oil, steam, water, wastewater, and nearly any other fluid conveyed by pipes. Generally, strainers are installed ahead of valves, pumps, regulators, and traps in order to protect them against the damaging effects of corrosion products that may become dislodged and conveyed throughout the piping system.

A common strainer is shown in Figure 8.38. This type of strainer is generally used upstream of traps, control valves, and instruments. This strainer resembles a lateral branch fitting with the strainer element installed in the branch. The end of the lateral branch is removable to permit servicing of the strainer.

In operation, the fluid passes through the strainer screen, which catches most of the contaminants. Then the fluid passes back into the line. Contaminants in the fluid are caught in two ways. Either they do not make it through the strainer screen, or they do not make the sharp turn that the fluid must take as it leaves the unit. The bottom of the unit serves as a sump where the solids collect. A blowout connection may be provided in the end cap to flush the strainer. The blowout plug can be removed, and the pressure in the line can be used to blow the fixture clean.

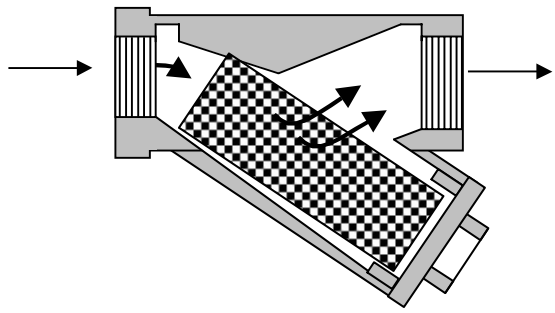

FIGURE 8.38 A common strainer. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Important Point: Before removing the blowout plug, the valve system must be locked out or tagged out first.

8.9.3 Filters

The purpose of any filter is to reduce or remove impurities or contaminants from a fluid (liquid or gas) to an acceptable or predetermined level. This is accomplished by passing the fluid through some kind of porous barrier. Filter cartridges have replaceable elements made of paper, wire cloth, nylon cloth, or fine-mesh nylon cloth between layers of coarse wire. These materials filter out unwanted contaminants that collect on the entry side of the filter element. When clogged, the element is replaced.

Most filters operate in two ways: (1) they cause the fluid to make sharp changes in direction as it passes through (this is important because the larger particles are too heavy to change direction quickly); and (2) they contain some kind of barrier that will not let larger contaminants pass.

8.9.4 Traps[43]

Traps, used in steam processes, are automatic valves that release condensate (condensed steam) from a steam space while preventing the loss of live steam. Condensate is undesirable because water produces rust and water plus steam leads to water hammer. In addition, steam traps remove air and noncondensate from the steam space.

The operation of a trap depends on what is called differential pressure (or delta-P), in pounds per square inch. Differential pressure is the difference between the inlet and outlet pressures. A trap will not operate correctly

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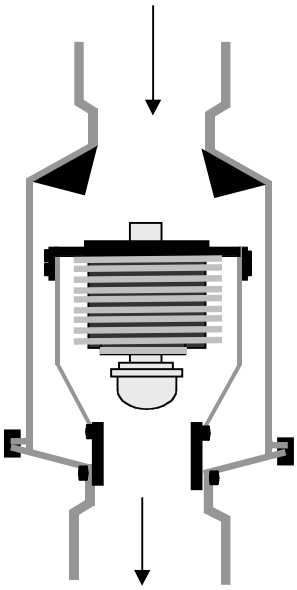

FIGURE 8.39 A thermostatic trap (shown in the open position). (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

at a differential pressure higher than the one of which it was designed.

There are many types of steam traps because there are many different types of applications. Each type of trap has a range of applications for which it is best suited. For example, thermostatic and float-and-thermostatic are the names given to the two general types of traps.

Thermostatic traps have a corrugated bellows-operating element that is filled with an alcohol mixture that has a boiling point lower than that of water (see Figure 8.39). The bellows contracts when in contact with condensate and expands when stream is present. If a heavy condensate load occurs, the bellows will remain in the contracted state, allowing condensate to flow continuously. As steam builds up, the bellows closes. At times the trap acts as a continuous flow type, while at other times it acts intermittently as it opens and closes to condensate and stream, or it may remain totally closed.

Important Point: The thermostatic trap is designed to operate at a definite temperature drop a certain number of degrees drop below the saturated temperature for the existing steam pressure.

A float-and-thermostatic trap is shown in Figure 8.40. It consists of a ball float and a thermostatic bellows element. As condensate flows through the body, the float rises and falls, opening the valve according to the flow rate. The thermostatic element discharges air from the steam lines. They are suitable in heavy and light loads and on high and low pressure, but are not recommended where water hammer is a possibility.

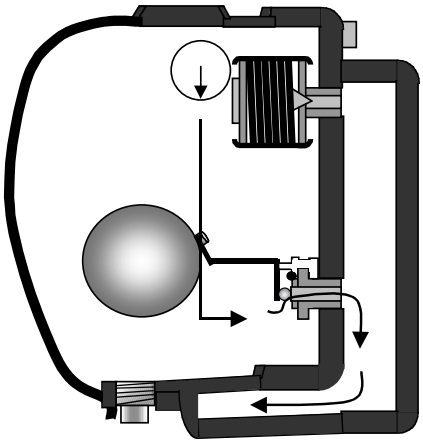

FIGURE 8.40 A float-and-thermostatic trap. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

8.9.4.1 Trap Maintenance and Testing

Because they operate under constantly varying pressure and temperature conditions, traps used in steam systems require maintenance. Just as significant, traps can fail due to these varying conditions. When they do fail, most traps fail in the open mode, which may require the boiler to work harder to perform a task that, in turn, can create high backpressure to the condensate system. This inhibits discharge capacities of some traps, which may be beyond their rating and cause system inefficiency.

Important Point: While it is true that most traps operate with backpressure, it is also true that they do so only at a percentage of their rating, affecting everything down the line of the failed trap. Steam quality and product can be affected.

A closed trap produces condensate back up into the steam space. The equipment cannot produce the intended heat. Consider, as an example, a four-coil dryer with only three coils operating. In this setup, it will take longer for the dryer to dry a product, which has a negative effect on production.

8.9.4.1.1 Trap Maintenance

Excluding design problems, two of the most common causes of trap failure are oversizing and dirt. Oversizing causes traps to work too hard. In some cases, this can result in blowing of live steam. For example, certain trap types can lose their prime due to an abrupt change in pressure. This will cause the valve to open.

Traps tend to accumulate dirt (sludge) that prevents tight closing. The moving parts of the traps are subject to wear. Because the moving parts of traps operate in a mixture of steam and water, or sometimes in a mixture of compressed air and water, they are difficult to lubricate.

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Important Point: Dirt (sludge) is generally produced from pipe scale or from overtreating of chemicals in a boiler.

Trap maintenance includes periodic cleaning, removing dirt that interferes with valve action, adjusting the mechanical linkage between moving parts and valves, and reseating the valves when necessary. If these steps are not taken, the trap will not operate properly.

8.9.4.1.2 Trap Testing

Important Point: A word of caution is advised before testing any steam trap: Inspectors should be familiar with the particular function, review types of traps and know the various pressures within the system. This can help to ensure inspector safety, help avoid misdiagnosis, and allow proper interpretation of trap conditions.

There are three main categories of online trap inspection: visual, thermal, and acoustic. Visual inspection depends on a release valve situated downstream of certain traps. A maintenance operator opens these valves and looks to see if the trap is discharging condensate or steam. Thermal inspection relies on upstream or downstream temperature variations in a trap. It includes pyrometry, infrared, heat bands (wrapped around a trap, they change color as temperature increases), and heat sticks (which melt at various temperatures). Acoustic techniques require a maintenance operator to listen to and detect steam trap operations and malfunction. This method includes various forms of listening devices such as medical stethoscopes, screwdrivers, mechanical stethoscopes, and ultrasonic detection instruments.

Important Point: A simple trap test, which involves just listening to the trap action, tells us how the trap is opening and closing. Moreover, if the trap has a bypass line around it, leaky valves will be apparent when the main line to the trap is cut off, forcing all the fluid through the bypass.

8.10 PIPING ANCILLARIES

Earlier we described various devices associated with process piping systems designed to protect the system. In this section, we discuss some of the most widely used ancillaries (or accessories) designed to improve the operation and control the system. These include pressure and temperature gauges, vacuum breakers, accumulators, receivers, and heat exchangers. It is important for us to know how these ancillary devices work, how to care for them, and, more importantly, how to use them.

8.10.1 GAUGES

To properly operate a system, any system, the operator must know certain things. For example, to operate a plant air compressor, the operator needs to know: (1) how to operate it; (2) how to maintain it; (3) how to monitor its operation; and, in many cases, (4) how to repair it. In short, the operator must know system parameters and how to monitor them.

Simply, operating parameters refer to those physical indications of system operation. The term parameter refers to a system's limits or restrictions. For example, consider, again, the plant's air compressor. It is important to know how the air compressor operates, or at least how to start and place the compressor on line properly. It is also equally important to determine if the compressor is operating per design.

Experienced operators know that in order to ensure that the air compressor is operating correctly (i.e., as per design), they need to monitor its operation. Again, they do this by monitoring the air compressor's operation by observing certain parameters. Before starting any machine or system we must first perform a pre-start check to ensure that it has the proper level of lubricating oil, etc. Then after starting the compressor, we need to determine (observe) if the compressor is actually operating (normally, this is not difficult to discern considering that most air compressor systems make a lot of noise while in operation). Once in operation, our next move is to double-check system line-up to ensure that various valves in the system are correctly positioned (opened or closed). We might even go to a remote plant compressed air service outlet to make sure that the system is producing compressed air. (Note: Keep in mind that some compressed air systems have a supply of compressed air stored in an air receiver; when an air outlet is opened, air pressure might be present even if the compressor is not functioning as per design.) On the other hand, instead of using a remote outlet to test for compressed air supply, all we need do is look at the compressor air pressure gauge. This gauge should indicate that the compressor is producing compressed air.

Gauges are the main devices that provide us with parameter indications that we need to determine equipment or system operation.

Concerning the air compressor, the parameter we are most concerned about now is air pressure (gauge pressure). Not only is correct pressure generation by the compressor important, but correct pressure in system pipes, tubes, and hoses is also essential. Keeping air pressure at the proper level is necessary mainly for four reasons:

1. Safe operation
2. Efficient, economic conveyance of air through the entire system, without waste of energy

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3. Delivery of compressed air to all outlet points in the system (the places where the air is to be used) at the required pressure
4. Prevention of too much or too little pressure (either condition can damage the system and become hazardous to personnel)

We pointed out that before starting the air compressor, certain prestart checks must be made. This is important for all machinery, equipment, and systems. In the case of our air compressor example, we want to ensure that proper lubricating oil pressure is maintained. This is important because pressure failure in the lubricating line that serves the compressor can mean inadequate lubrication of bearings, and, in turn, expensive mechanical repairs.

8.10.1.1 Pressure Gauges

As mentioned, many pressure-measuring instruments are called gauges. Generally, pressure gauges are located at key points in piping systems. Usually expressed in pounds per square inch, there is a difference between gauge pressure (psig) and absolute pressure (psia). Simply, gauge pressure refers to the pressure level indicated by the gauge. However, even when the gauge reads zero, it is subject to ambient atmospheric pressure (i.e., 14.7 psi at sea level). When a gauge reads 50 psi that is 50 lb gauge pressure (psig). The true pressure is the 50 pounds shown plus the 14.7 lb of atmospheric pressure acting on the gauge. The total of "actual" pressure is called the absolute pressure: gauge pressure plus atmospheric pressure (50 psi + 14.7 psi = 64.7). It is written 64.7 psia.

Important Point: Pressure in any fluid pushes equally in all directions. The total force on any surface is the pounds per square inch multiplied by the area in square inches. For example, a fluid under a pressure of 10 psi, pushing against an area of 5 in,^{2} produces a total force against that surface of 50 lb (10×5).

8.10.1.1.1 Spring-Operated Pressure Gauges

Pressure, by definition, must operate against a surface. The most common method of measuring pressure in a piping system is to have the fluid press against some type of surface — a flexible surface that moves slightly. This movable surface is linked mechanically to a gear-lever mechanism that moves the indicator arrow to indicate the pressure on the dial (i.e., a pressure gauge).

The surface that the pressure acts against may be a disk or diaphragm, the inner surface of a coiled tube, a set of bellows, or the end of a plunger. No matter the element type, if the mechanism is fitted with a spring that resists the pressure and returns the element (i.e., the indicator pointer) back to the zero position when the spring drops to zero, it is called a spring-loaded gauge.

8.10.1.1.2 Bourdon-Tube Gauges

Many pressure gauges in use today use a coiled tube as a measuring element called a Bourdon tube. (The gauge is named for its inventor, Eugene Bourdon, a French engineer.) The Bourdon tube is a device that senses pressure and converts the pressure to displacement. Under pressure, the fluid fills the tube (see Figure 8.41). Since the Bourdon-tube displacement is a function of the pressure applied, it may be mechanically amplified and indicated by a pointer. Thus, the pointer position indirectly indicates pressure.

Important Point: The Bourdon-tube gauge is available in various tube shapes: helical, C-shaped or curved, and spiral. The size, shape, and material of the tube depend on the pressure range and the type of gauge desired.

8.10.1.1.3 Bellows Gauge

Figure 8.42 shows how a simplified bellows gauge works. The bellows is a convoluted unit that expands and contracts axially with changes in pressure. The pressure to be measured can be applied to either the outside or the inside of the bellows; in practice, most bellows measuring devices have the pressure applied to the outside of the bellows. When pressure is released, the spring returns the bellows and the pointer to the zero position.

8.10.1.1.4 Plunger Gauge

Most of us are familiar with the simple tire-pressure gauge. This device is a type of plunger gauge. Figure 8.43 shows a plunger gauge used in industrial hydraulic systems. The bellows gauge is a spring-loaded gauge, where pressure from the line acts on the bottom of a cylindrical plunger in the center of the gauge and moves it upward. At full pressure, the plunger extends above the gauge, indicating the measured pressure. As the pressure drops, the spring contracts to pull the plunger downward, back into the body (the zero reading indication).

Note: Spring-loaded gauges are not extremely accurate, but they are entirely adequate where there is no need for more precise readings.

8.10.1.1.5 Temperature Gauges

As mentioned, ensuring that system pressures are properly maintained in equipment and piping systems is critical to safe and proper operation. Likewise, ensuring that the temperature of fluids in industrial equipment and piping systems is correct is just as critical. For measuring the temperature of fluids in industrial systems, various temperature-measuring devices are available.

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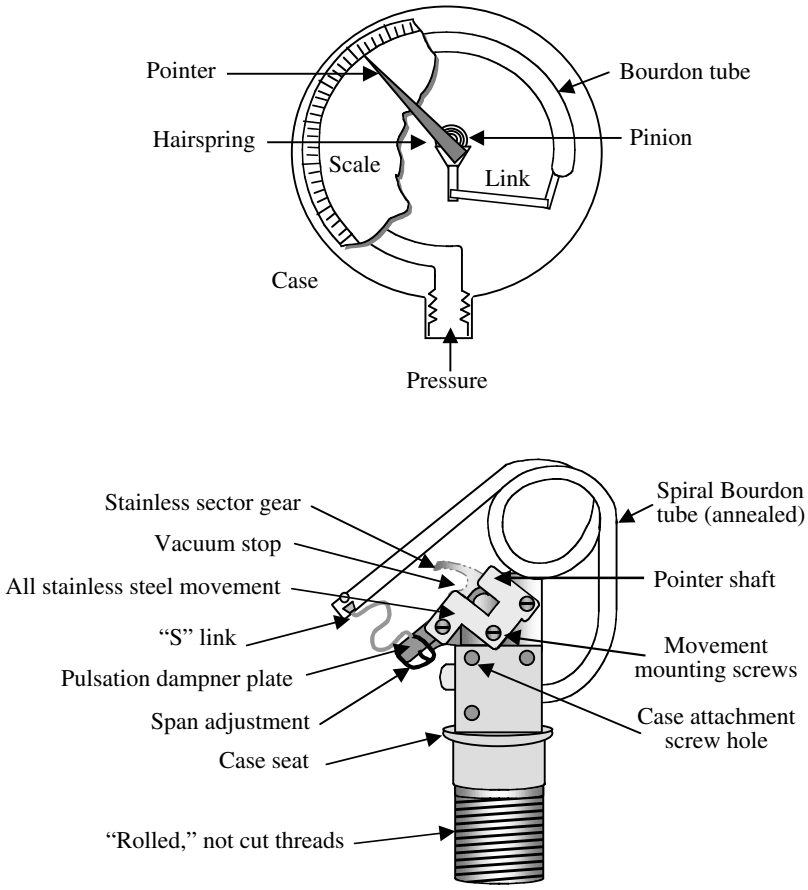

FIGURE 8.41 (Top) Bourdon tube gauge; (bottom) internal components. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

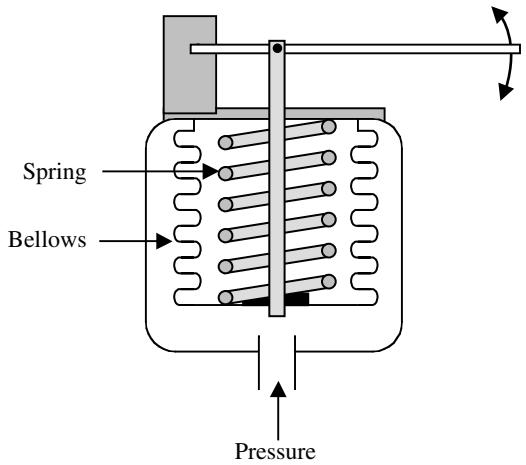

FIGURE 8.42 Bellows gauge. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

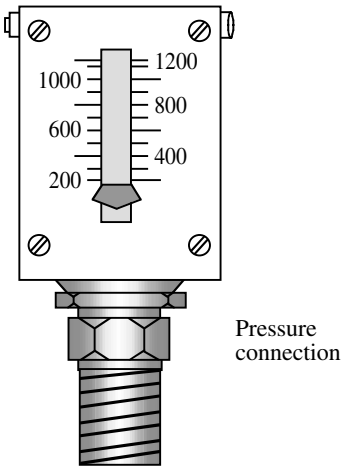

FIGURE 8.43 Plunger gauge. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

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Temperature has been defined in a variety of ways. One example defines temperature as the measure of heat (thermal energy) associated with the movement (kinetic energy) of the molecules of a substance. This definition is based on the theory that molecules of all matter are in continuous motion that is sensed as heat.

For our purposes, we define temperature as the degree of hotness or coldness of a substance measured on a definite scale. Temperature is measured when a measuring instrument is brought into contact with the medium being measured (e.g., a thermometer). All temperature-measuring instruments use some change in a material to indicate temperature. Some of the effects that are used to indicate temperature are changes in physical properties and altered physical dimensions (e.g., the change in the length of a material in the form of expansion and contraction).

Several temperature scales have been developed to provide a standard for indicating the temperatures of substances. The most commonly used scales include the Fahrenheit, Celsius, Kelvin, and Rankine temperature scales. The Celsius scale is also called the centigrade scale.

The Fahrenheit (ºF) and Celsius (ºC) scales are based on the freezing point and boiling point of water. The freezing point of a substance is the temperature that changes its physical state from a liquid to a solid. The boiling point is the temperate that a substance changes from a liquid state to a gaseous state.

Note: Thermometers are classified as mechanical temperature sensing devices because they produce some type of mechanical action or movement in response to temperature changes. There are many types of thermometers: liquid, gas, and vapor filled systems and bimetallic thermometers.

8.10.1.1.5.1 Industrial Thermometers

Figure 8.44 shows an industrial-type thermometer that is commonly used for measuring the temperature of fluids

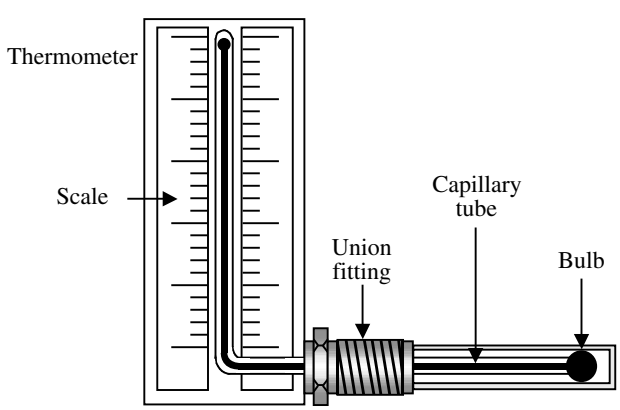

FIGURE 8.44 Industrial thermometer. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

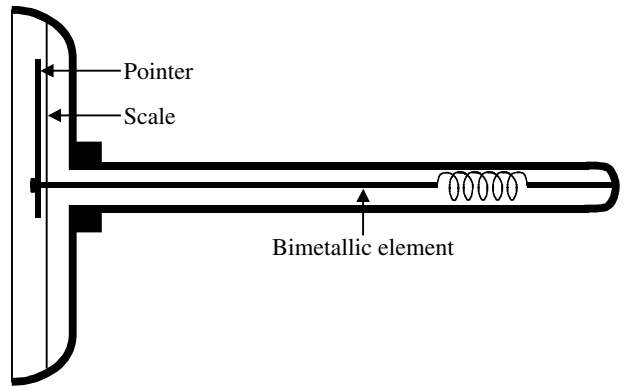

FIGURE 8.45 Bimetallic gauge. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

in industrial piping systems. This type of measuring instrument is nothing more than a rugged version of the familiar mercury thermometer. The bulb and capillary tube are contained inside a protective metal tube called a well. The thermometer is attached to the piping system (vat, tank, or other component) by a union fitting.

8.10.1.1.5.2 Bimetallic Gauge Thermometer

Another common type of temperature gauge is the bimetallic gauge shown in Figure 8.45. Bimetallic means that if two materials with different linear coefficients of expansion (i.e., how much a material expands with heat) are bonded together, as the temperature changes their rate of expansion will be different. This will cause the entire assembly to bend in an arc. When the temperature is raised, an arc is formed around the material with the smaller expansion coefficient. The amount of arc is reflected in the movement of the pointer on the gauge. Because two dissimilar materials form the assembly, it is known as a bimetallic element, which is also commonly used in thermostats.

8.10.2 Vacuum Breakers

Another common ancillary device found in pipelines is a vacuum breaker (components shown in Figure 8.46). Simply, a vacuum breaker is a mechanical device that allows air into the piping system, thereby preventing backflow that could otherwise be caused by the siphoning action created by a partial vacuum. In other words, a vacuum breaker is designed to admit air into the line whenever a vacuum develops. A vacuum, obviously, is the absence of air. Vacuum in a pipeline can be a serious problem. For example, it can cause fluids to run in the wrong direction, possibly mixing contaminants with purer solutions. (Note: In water systems, backsiphonage can occur when a partial vacuum pulls nonpotable liquids back into the supply lines.[44]) In addition, it can cause the collapse of tubing or equipment.

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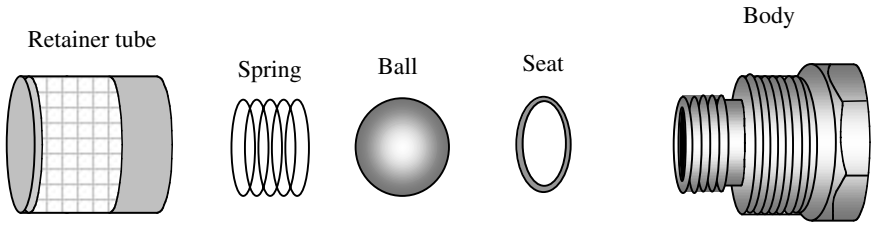

FIGURE 8.46 Vacuum breaker components. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

As illustrated in Figure 8.46, this particular type of vacuum breaker uses a ball that usually is held against a seat by a spring. The ball is contained in a retainer tube mounted inside the piping system or inside the component being protected. If a vacuum develops, the ball is forced (sucked) down into the retainer tube, where it works against the spring. Air flows into the system to fill the vacuum. (Note: In water systems, when air enters the line between a cross-connection and the source of the vacuum, then the vacuum will be broken and backsiphonage is prevented.[45]) The spring then returns the ball to its usual position, which acts to seal the system again.

8.10.3 Accumulators

As mentioned, in a plant compressed air system, a means of storing and delivering air as needed is usually provided. An air receiver normally accomplishes this. In a hydraulic system, an accumulator provides the functions provided by an air receiver for an air system. The accumulator (usually a dome-shaped or cylindrical chamber or tank attached to a hydraulic line) in a hydraulic system works to help store and deliver energy as required. Moreover, accumulators work to help keep pressure in the line smoothed out. For example, if pressure in the line rises suddenly, the accumulator absorbs the rise, preventing shock to the piping. If pressure in the line drops, the accumulator acts to bring it up to normal.

Important Point: The primary function of an accumulator in a hydraulic system is to supplement pump flow.

8.10.4 Air Receivers

As shown in Figure 8.47, an air receiver is a tank or cylindrical-type vessel used for a number of purposes. Most important is their ability to store compressed air. Much like accumulators, they cushion shock from sudden pressure rises in an airline. The air receiver serves to absorb the shock of valve closure and load starts, stops, and reversals. There is no liquid in an air receiver. The air compresses as pressure rises. As pressure drops, the air expands to maintain pressure in the line.

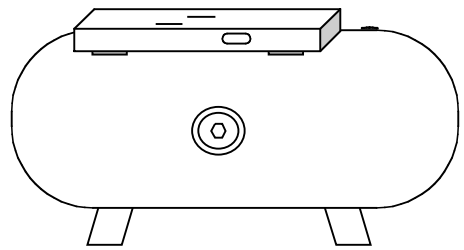

FIGURE 8.47 Air receiver. (From Spellman, F.R. and Drinan, J., *Piping and Valves,* Technomic Publ., Lancaster, PA, 2001.)

Important Note: OSHA has a standard, 29 CFR 1910.169(a), requiring air receivers be drained. Specifically, the standard states, "a drain pipe and valve shall be installed at the lowest point of every air receiver to provide for the removal of accumulated oil and water."[46] This is an item that should be taken seriously, not only for safety reasons, but also because it is a compliance item that OSHA inspectors often check.

8.10.5 Heat Exchangers

Operating on the principle that heat flows from a warmer body to a cooler one, heat exchangers are devices used for adding or removing heat and cold from a liquid or gas. The purpose may be to cool one body or warm the other; nonetheless, whether used to warm or to cool, the principle remains the same. Various designs are used in heat exchangers. The simplest form consists of a tube, or possibly a large coil of tubing, placed inside a larger cylinder. In an oil lubrication system, the purpose of a heat exchanger is to cool the hot oil. A heat exchanger system can also be used to heat up a process fluid circulating through part of the heat exchanger while steam circulates through its other section.

Final Note: In this section, we have discussed the major ancillary or accessory equipment used in many piping systems. It is important to point out that there are other accessories commonly used in piping systems (e.g., rotary pressure joints, actuators, intensifiers, pneumatic pressure

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line accessories, and so forth); however, discussion of these accessories is beyond the scope of this text.

8.11 CHAPTER REVIEW QUESTIONS AND PROBLEMS

8.1. What is an expansion joint?
8.2. A _____ is defined as any substance or material that flows.
8.3. Compressed air is considered to be a _____.
8.4. Sections or lengths of pipe are _____ with fittings.
8.5. The _____ of fluids through a pipe is controlled by valves.
8.6. Friction causes _____ in a piping system.
8.7. As friction _____ in a piping system, the output pressure decreases.
8.8. Relief valves are designed to open _____.
8.9. _____ is used to help keep the fluids carried in piping systems hot or cold.
8.10. The major problems in piping systems are caused by _____ and corrosion.
8.11. If the speed of fluid in a pipe doubled, the friction is _____.
8.12. The most important factor in keeping a piping system operating efficiently is _____.
8.13. Pipe sizes above _____ in. are usually designated by outside diameter.
8.14. The difference in _____ numbers represents the difference in the wall _____ of pipes.
8.15. When pipe wall thickness _____, the I.D. decreases.
8.16. A _____ metal contains iron.
8.17. As temperature _____, the viscosity of a liquid decreases.
8.18. What is another name for rust?
8.19. Sections of _____ water pipe are usually connected with a bell-and-spigot joint.
8.20. A ferrous metal always contains _____.
8.21. Asbestos-cement pipe has the advantage of being highly resistant to _____.
8.22. As temperature increases, the strength of plastic pipe _____.
8.23. Name four basic nonmetallic piping materials.
8.24. Vitrified clay pipe is the most _____ pipe available for carrying industrial wastes.
8.25. Cast iron pipe can be lined with _____ to increase its resistance to corrosion.
8.26. A joint made so that the sections of tubing are _____ together is called a compression joint.
8.27. Incorrect tube bends can cause _____ flow and _____ pressure.
8.28. High-pressure hydraulic systems use _____ tubing.
8.29. One process used to join plastic tubing is called _____ welding.
8.30. Compared to pipe, tubing is more _____.
8.31. _____ tubing is most likely used in food-processing applications.
8.32. Before tubing can be bent or flared, it should be _____.
8.33. Plastic tubing is usually joined by _____.
8.34. The materials used most commonly for tubing are _____ and _____.
8.35. Smooth fluid flow is called _____ flow.
8.36. The _____ hose is the most common type of hose in general use.
8.37. The type of hose construction most suitable for maximum suction conditions is _____.
8.38. _____ is the nonmetallic hose best suited for use at extremely low temperatures.
8.39. Each size of hose clamp is designed for a hose of a specific _____.
8.40. _____ is the outstanding advantage of hose.
8.41. Applied to a hose, the letters _____ stand for enlarged end.
8.42. A hose is _____ in order to provide strength and greater resistance to _____.
8.43. The Dacron hose remains _____ at extremely low temperatures.
8.44. The _____ fitting allows for a certain amount of pipe movement.
8.45. The _____ fitting helps reduce the effects of water hammer.
8.46. A flange that has a plain face should be joined to a flange that has a _____ face.
8.47. Improperly made _____ restrict fluid flow in a pipeline.
8.48. The designation 200 lb refers to the _____ at which a fitting can safely be used.
8.49. Used to close off an unused outlet in a fitting with a _____.
8.50. A _____ connects two or more pipes of a different diameter.
8.51. A _____ is used to make a pressure-tight joint between _____ has a more gradual curve than does the short-radius elbow.

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8.52. _____ control fluid flow through piping systems.

8.53. Valves can be used to _____, _____, and _____ flow.

8.54. A _____ valve is better suited for throttling service than is a gate valve.

8.55. A _____ valve is a fast-operating shut-off valve commonly used in large water-circulating systems.

8.56. A pressure regulating valve keeps the _____ at a _____ level.

8.57. _____ in a fluid line can clog the closing element of a valve.

8.58. Before removing a strainer for cleaning, the line should be _____.

8.59. Because steam traps operate in a mixture of steam and water it is often difficult to _____ steam traps.

8.60. Steam traps are used to remove _____ or _____ from steam lines.

8.61. _____ is steam that condenses into water in a piping system.

8.62. _____ pressure is equal to gauge pressure plus atmospheric pressure.

8.63. _____ pressure gauges do not provide extremely accurate readings.

8.64. The value that represents how much a material _____ is called the coefficient of expansion.

8.65. The purpose of a _____ is to admit air into the system.

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9 Flow Measurement

Water is the best of all things.

Pindar (C. 522–C. 438 B.C.E) ***Olympian Odes***

Flow is measured…one cannot afford not to measure…because the competitive environment dictates that one does "not" have the luxury of producing "wastefully." Someone is always watching; if not the plant manager, then the vice-president of finance; if not the plant neighbors, then the EPA; and, of course, there are laws of physics to keep everyone honest.[1]

9.1 INTRODUCTION

Flow is one of the most difficult variables to measure accurately. If we wanted to use an approximate (but very simple) method to determine open channel discharge, we would measure the velocity of a floating object moving in a straight uniform reach of the channel. If we know the cross-sectional geometry of the channel and the depth of flow is determined, we can compute the flow area. From the relationship $Q = A \times V$, we can estimate the discharge Q. The average velocity of flow in a reach is approximated by timing the passage of the floating object along a measured length of channel.

While it is a useful way to obtain a ballpark estimate for the flow rate as part of a preliminary field study, this technique is not suitable for routine measurements required in water and wastewater treatment plant operations.

Another simple (but impractical) method of determining flow is the weight per unit time method. This method assumes a basic premise of fluid mechanics: mass is a conserved quantity. Simply, the mass entering a system is equal to the mass leaving the system when both are measured over the same time interval. Using the weight per unit time method to measure flow requires catching the flow in a container and weighing it over a given interval of time. The impracticality of using this method in water and wastewater operations can be seen in closed-loop processes commonly associated with chemical applications. Consequently, other methods must be used to obtain flow measurements.

Any seasoned water and wastewater operator knows that *flow measurement* is an essential part of water and wastewater treatment. Unit processes are designed for specific flow levels, and process adjustments (e.g., adjustments made on pumping rates, chlorination rates, filter rates, aeration rates, etc.) are based upon current levels of flow; in many cases, they are controlled by flow rate adjustments. Accurate flow measurement is a key element in any attempt to identify, correct, and prevent operational problems. Therefore, it is important to operators tasked with operating the plant at optimal efficiency.

In this chapter, we briefly discuss methods of measuring flow, many of the calculations used to determine flow, and various flow measurement problems.

9.2 METHODS OF MEASURING FLOW

Measuring the flow in water and wastewater operations requires a thorough, detailed understanding of the process and the substance being measured. Two factors that determine the method of flow measurement and the flowmeter most suited to an application are the quantity of the flow and the type of substance being measured.

We already mentioned one of the methods of measuring flow, using the $Q = A \times V$ formula method. When using this method, we measure the velocity of the flow and the channel width/water depth first, then the formula is used to find flow rate. This procedure can be used in any location where you can measure the water cross-sectional area and velocity.

Note: The flow rate of a substance can be described using a number of terms including feet per second, gallons per minute, cubic feet per minute, and tons per hour. The unit chosen to indicate flow rate is an important factor in flow measurement applications, and varies according to the indicating requirements specific to the process.

Another simple method that can be used to measure flow is known as the fill and draw method. Accomplished by measuring the amount of time required to transfer or pump a given volume of water from one point to another, use the fill and draw method at any location where changes in liquid volume (or depth) can be measured.

From the description of the two rudimentary measurement techniques just described, we can see that even in those cases where flow measurement is provided, some method can be found to measure — or at least estimate — flow rates. However, the majority of water and wastewater operators do not measure flow by the two methods. Instead, modern treatment plants and current practices normally include the use of other methods. For example, the bucket and stopwatch technique has been replaced with other methods, up to and including complex electronic systems.

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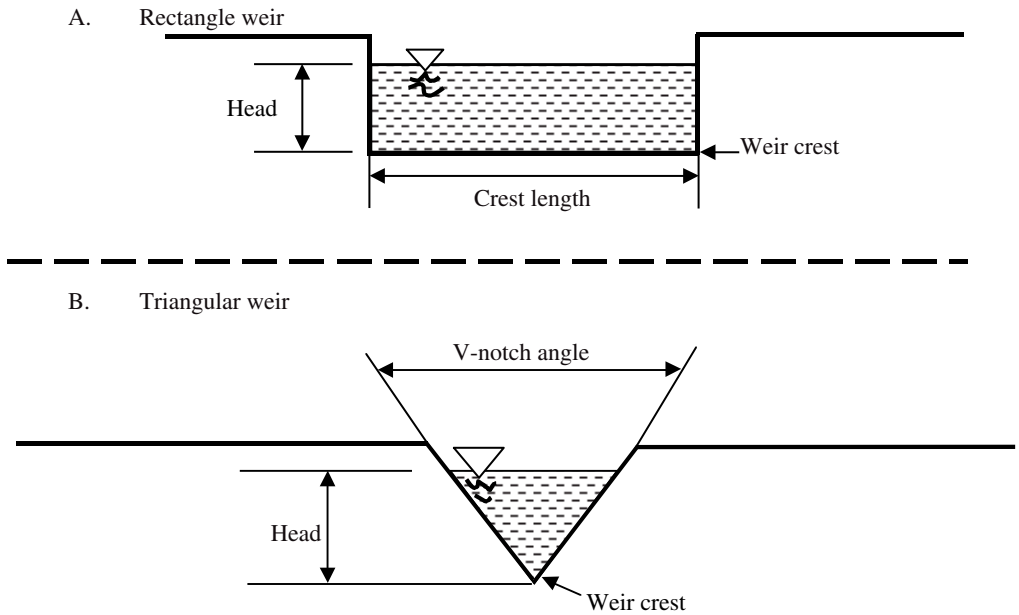

FIGURE 9.1 (A) Rectangular weir; (B) triangular V-notch weir. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

9.2.1 Weirs

The simplest, least expensive, and probably the most common type of primary measuring device used to measure flow in open channels is the weir. A weir is simply a dam, rectangular obstruction, or V-notch crest (over which water flows), placed in the channel so that the water backs up behind it and then flows over it (see Figure 9.1-A and Figure 9.1-B). For open channel measurements, weirs can be used for rectangular and circular clarifiers (see Figure 9.2). The crest or edge allows the water to spring clear of the weir plate and to fall freely into the air. Each type of weir has an associated equation for determining the flow rate through the weir. The equation is based on the depth of the liquid in the pool formed upstream from the weir. Simply, in measuring, measure the head a specified distance behind the weir (constriction) in the channel, and then use the head to calculate the flow or to determine the flow using a table or graph.

The edge or surface over which the water passes is called the crest of the weir, as shown in Figure 9.1-A. Generally, the top edge of the weir is beveled with a sharp upstream corner (aptly called sharp-crested weirs) so that the liquid does not contact any part of the weir structure downstream, but rather springs past it. This stream of water leaving the weir crest is called the nappe. A disadvantage of a weir is the relatively dead water space that occurs just upstream of the weir where organic solids may settle out, causing odors.

Note: The operation of the weir is sensitive to any foreign material or debris that may be present upstream of the flowmeter or on the weir plate itself. Therefore, the weir should be periodically inspected and any accumulated debris removed. This action will also reduce organic settling, and thus reduce odors.

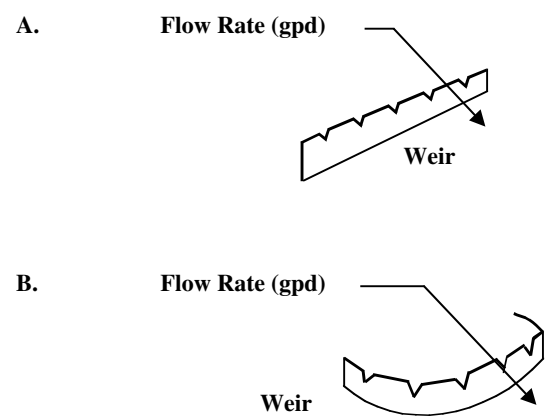

FIGURE 9.2 (A) Weir overflow for rectangular clarifier; (B) weir overflow for circular clarifier. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

9.2.2 The Oscillating Disk Water Meter

Many individual household and apartment dwellers are familiar with the oscillating disk water meter, even if they do not think they are. They at least they know that there is a meter that is read by the utility routinely and that their water bill is based on that meter reading.

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This standard household water meter is known as the oscillating disk water meter, which is a common positive-displacement meter. The meter has a measuring chamber of known volume containing a disk that goes through a cyclic motion as water passes through. A recording register, which can be mounted exterior to the house, records the rotation resulting from filling and emptying of the chamber. This type of meter is very reliable, simple in construction, highly sensitive, accurate, and has low maintenance costs.

Note: For customers requiring high flow rates, another type of water meter is used: the compound meter. The general-service compound meter consists of a positive-displacement, current meter with an automatic valve arrangement that directs water to the current meter during high rates of flow and to the displacement meter at low rates.

9.2.3 Flumes

Besides the weir, another device commonly used to measure flow in open channels is the flume. Figure 9.3 shows a Parshall flume — the most commonly used measuring device. The Parshall flume is named after Dr. Ralph L. Parshall formerly of the U.S. Soil Conservation Service. In 1922, Dr. Parshall modified the existing venturi flume design. This perfected device measures the head a specified distance behind the narrow point (throat of the flume), then the head measurement is used to calculate the flow or the flow is determined by using a table or graph. Because wastewater contains suspended and floating solids, it prohibits the use of enclosed meters. This is where the flume comes in. The principal advantages of the Parshall flume are its:

1. Capabilities for self-cleaning (i.e., its design and smooth construction does not offer any place where solids may collect behind the metering device)
2. Relatively low head loss
3. Ability to function over a wide operating range while requiring only a single head measurement.

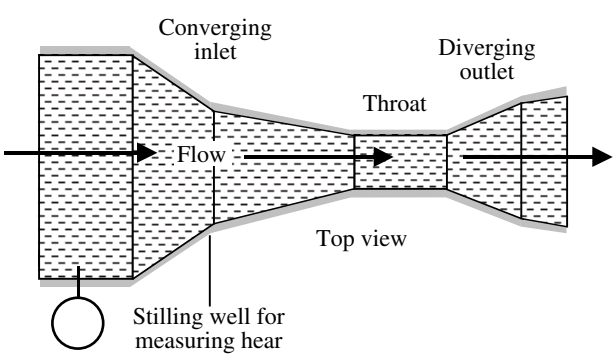

FIGURE 9.3 Parshall flume. (From Spellman, F.R. and Drinan, J., *Water Hydraulics,* Technomic Publ., Lancaster, PA, 2001.)

Again, these characteristics make it particularly suitable for flow measurement in wastewater operations. The flume is also used in water flow measurement applications.

9.2.4 Venturi Meter

A venturi is a restriction with a relatively long passage with smooth entry and exit. The venturi meter is another flow measuring device found in pipe systems in wastewater collection systems and treatment plants. It utilizes the principle of differential pressure — the flow must pass through a section with a smaller diameter in a device. The change in pressure that occurs while passing through the smaller diameter section is related to the rate of flow through the pipe. It is often used in wastewater streams since the smooth entry allows solids to be swept through instead of building up as it would in front of an orifice.

9.2.5 Magnetic Flowmeter

The magnetic meter (magmeter) is another flow measuring device commonly used to measure flow of the wastestream through pipes. In operation, wastewater is passed between the poles of a magnet. The flow creates an electrical current that the meter measures. The amount of current produced is related to the amount of flow.

With obstructionless design, there are no moving parts to wear and no pressure drop other than that offered by a section of pipe with equal length and inside diameter. Moreover, the magmeter has the advantages of a linear output, corrosion-resistant wetted parts, and highly accurate output. "The greatest disadvantage of this type of meter is its initial cost and the need for trained personnel to handle routine operation and maintenance."[2]

Table 9.1 provides a list of many different types of methods and devices applicable to fluid flow measurement.

9.3 FLOW MEASUREMENT CALCULATIONS

While it is true that flow can be measured electronically or by using various tables or charts, water and wastewater operators should be skilled in making flow computations. Even with the use of a chart or graph, appropriate conversions and calculations are required.

In this section, we discuss the calculations required to determine flow rates using the fill and draw, V-notch weir, and the Parshall flume. We also provide a few simple flow calculation problems.

9.3.1 Calculation Method Used for Fill and Draw Technique

The mathematical procedure for determining flow in gallons/minute is:

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TABLE 9.1
Types of Flow Measurement Devices

Devices	Typical Use[a]	Principle of Flow Measurement
		For Pressure Pipes
Elbow meter	w	The differential pressure is measured around a bend
Rotameter	w	The rise of float in a tapered tube is measured
Pitot tube	w	The differential pressure is measured
venturi meter	ww	The differential pressure is measured
Acoustic meter	ww	The sound waves are used to measure the velocity
Turbine meter	ww	A velocity driven rotational element (turbine, vane, wheel) is used
Electromagnetic meter	ww	Magnetic field is induced and voltage is measured
Orifice meter	ww	The differential pressure is measured
Flow nozzle meter	ww	The differential pressure is measured
		For Open Channels
Flumes	ww	Critical depth is measured at the flume
Weirs	ww	Head is measured over a barrier (weir)
Pitot tube	w	The differential pressure is measured
Current meter	w	Rotational element is used to measure velocity
Acoustic meter	ww	The sound waves are used to measure velocity and depth
Depth measurement	ww	Float is used to obtain the depth of flow

[a] w = water application; ww = wastestream application

Source: Adapted from Qasim, S.R., *Wastewater Treatment Plants: Planning, Design, and Operation*, Technomic Publ., Lancaster, PA, 1994, p. 221. With permission.

$$\text{Flow}\left(Q[\text{gal/min}]\right) = \frac{\text{Tank Volume}\left(\text{ft}^3\right) \times 7.48\ \text{gal/ft}^3}{\text{Time Required (min)}} \tag{9.1}$$

9.3.2 Calculation Method Used for Velocity/Area Technique

For determining flow in cubic feet per second or gallons per minute using the velocity/area technique, the following equations can be used:

$$Q\left(\text{ft}^3/\text{sec}\right) = \text{Channel Width (ft)} \times \text{Water Depth (ft)} \times V\left(\text{ft/sec}\right) \tag{9.2}$$

$$Q\left(\text{gal/min}\right) = \frac{Q\left(\text{ft}^3/\text{sec}\right) \times 1{,}000{,}000}{1.55\ \text{ft}^3/\text{sec/MGD} \times 1440\ \text{min/d}} \tag{9.3}$$

9.3.3 Calculation Method Used for V-Notch Weirs

Use a chart or graph and make appropriate conversions, then use the following equation:

$$Q\left(\text{ft}^3/\text{sec}\right) = K \times H^{2.5} \tag{9.4}$$

where

H = Head in feet
K = Constant related to the weir angle

Weir	Constant
22.5°	0.497
30°	0.676
45°	1.035
60°	1.443
90°	2.500
120°	4.330

9.3.4 Weir Overflow (Weir Loading Rate)

Weir overflow rate is the effluent flow rate expressed in gallons per linear foot of weir per day (see Figure 9.2). It can be used to evaluate actual operating conditions by comparing current values with design specifications.

$$\text{Weir Overflow} = \frac{Q\left(\text{gal/d}\right)}{\text{Weir Length (ft)}} \tag{9.5}$$

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EXAMPLE 9.1

Problem:

The circular settling tank is 90 ft in diameter and has a weir along its circumference. The effluent flow rate is 2.50 MGD. What is the weir overflow rate in gallons per day in feet?

Solution:

$$\text{Weir Overflow} = \frac{2.50 \times 1{,}000{,}000 \text{ gal/MG}}{3.14 \times 90 \text{ ft}}$$

$$= 8846.4 \text{ gal/d/ft}$$

9.3.5 CALCULATION METHOD FOR PARSHALL FLUME

As with the V-notch weir, calculating flow through a Parshall Flume requires the use of charts or graphs and appropriate conversions. Then, the following equations may be used.

1. For flume throats less than 12 in. wide

$$Q\left(\text{ft}^3/\text{sec}\right) = K \times H^n \tag{9.6}$$

where
K = Constant related to the throat width

3 in.	0.9920
6 in.	2.060
9 in.	3.070

n = exponent constant related to throat width

3 in.	1.547
6 in.	1.580
9 in.	1.530

2. For flume throats 1 to 8 ft wide

$$Q\left(\text{ft}^3/\text{sec}\right) = 4 \times W \times H^{1.522L} \tag{9.7}$$

where
W = Throat width
$L = W^{0.026}$

9.3.6 TYPICAL FLOW MEASUREMENT PRACTICE CALCULATIONS

The answers to the examples provided in this section are derived using equation standard **Q = AV**, including conversions where appropriate.

EXAMPLE 9.2

Problem:

A grit channel 3 ft wide has water flowing to a depth of 16 in. If the velocity through the channel is 0.8 ft/sec, what is the ft^3/sec flow rate through the channel?

Solution:

$$3 \text{ ft} \times 1.3 \text{ ft} \times 0.8 \text{ ft/sec} = 3.12 \text{ ft}^3/\text{sec}$$

EXAMPLE 9.3

Problem:

A grit channel 3 ft wide has water flowing at a velocity of 1.3 ft/sec. If the depth of water is 15 in., what is the gal/d flow rate through the channel?

Solution:

$$3 \text{ ft} \times 1.25 \text{ ft} \times 1.3 \text{ ft/sec} \times 7.48 \text{ gal/ft}^3 \times$$

$$60 \text{ sec/min} \times 1440 \text{ min/d} = 3{,}150{,}576 \text{ gal/d}$$

EXAMPLE 9.4

Problem:

A grit channel 35 in. wide has water flowing to a depth of 9 in. If the velocity of the water is 0.80 fps, what is the ft^3/sec flow in the channel?

Solution:

$$2.9 \text{ ft} \times 0.75 \text{ ft} \times 0.80 \text{ ft/sec} = 1.74 \text{ ft}^3/\text{sec}$$

9.4 FLOW MEASUREMENT OPERATIONAL PROBLEMS

Operators are often responsible for troubleshooting flow measurement problems. Our experience indicates that flow measurement problems (indicative of problems with the flow measuring method or device used) typically fall into two categories: (1) a sharp drop or increase in recorded flow, or (2) inconsistent or inaccurate flow measurement using a weir.

A number of causes could be responsible for a sharp drop or increase in recorded flow. For example, the problem could be caused by an obstruction to the float (if used). Removing the obstruction and/or keeping the float clean and free of grease correct this problem. Another type of flow measuring device may malfunction because of improper airflow or a damaged bubbler tube. In correcting this problem, the bubbler tube should be cleaned, the airflow adjusted, and grease removed from the assembly.

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In another type of measuring device, the problem might be indicative of grease buildup on magnetic meter coils. Solving this problem is a simple matter of removing grease buildup. A weir plate clogged with debris could also cause a sharp drop in recorded flow. To correct this problem, debris should be removed and the frequency of weir cleaning should be increased.

Inconsistent or frequent inaccurate flow measurement using a weir usually indicates that the weir is not level and needs to be adjusted.

9.5 CHAPTER REVIEW QUESTIONS AND PROBLEMS

9.1. Why are flow measurements important?

9.2. A grit channel 2.5 ft wide has water flowing to a depth of 18 in. If the velocity of the water is 0.8 ft/sec, what is the ft^3/sec flow in the channel?

9.3. A grit channel is 2.5 ft wide with water flowing to a depth of 15 in. If the flow velocity through the channel is 1.6 ft/sec, what is the gal/min flow through the channel?

9.4. A grit channel 3 ft wide has water flowing to a depth of 10 in. If the velocity through the channel is 1 ft/sec, what is the ft^3/sec flow rate through the channel?

9.5. If you had the choice of installing a weir system or a Parshall flume flow measurement device in your plant, which one would you choose or prefer? Why?

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Part III

Characteristics of Water

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10 Basic Water Chemistry

The waterworks or wastewater treatment plant operator lacking in knowledge of basic water chemistry and standard laboratory procedures is like the auto mechanic who does not know how to operate an engine analyzer and/or how to interpret the results of such analysis.

10.1 INTRODUCTION

As the chapter opening suggests, water and wastewater operators both perform and analyze the results of laboratory tests. Because of this, they must have a working knowledge of water chemistry. In this chapter, we discuss basic water chemistry — the key word is basic. Not all water and wastewater operators must be chemists, but they all must be able to perform very basic chemical testing. More importantly, all water and wastewater operators must be competent operators — basic knowledge of water chemistry fundamentals aids in attaining competency.

In the excellent text, *Water and Wastewater Laboratory Techniques*, R.L. Smith points out that chemical testing can be divided into two types.

"The first type measures a bulk physical property of the sample, such as volume, temperature, melting point, or mass. These measurements are normally performed with an instrument, and one simply has to calibrate the instrument to perform the test. Most analyses, however, are of the second type, in which a chemical property of the sample is determined that generates information about how much of what is present."[1]

When it comes to actually studying water at its most basic elementary level, you first must recognize that no one has ever seen a molecule of water. All that is available to us is equations and theoretical diagrams. When we look at the H_2O formula, we instantly think that water is simple. It is a mistake to think of water as being simple. It is not — it is very complex.

Although no one has seen a water molecule, we have determined through x-rays that atoms in water are elaborately meshed. Moreover, although it is true that we do not know as much as we need to know about water — our growing knowledge of water is a work in progress — we have determined many things about water. A large amount of our current knowledge comes from studies of water chemistry.

Water chemistry is important because several factors about water that is to be treated and then distributed or returned to the environment are determined through simple chemical analysis. Probably the most important determination that the water operator makes about water is its hardness. The wastewater operator, on the other hand, uses chemistry to determine other factors. For example, the wastewater operator may be interested in some of the same chemical results as water operators, but also must determine the levels of organics in the waste stream.

Why chemistry? "I am not a chemist," you say.

Simply, when you add chlorine to water to make it safe to drink or safe to discharge into a receiving body (usually a river or lake), you are a chemist. Chemistry is the study of substances and the changes they undergo. This chapter covers the fundamentals of chemistry specific to water and/or wastewater practices.

Before beginning our discussion of water chemistry, it is important for the reader to have some basic understanding of chemistry concepts and chemical terms. Thus, the following section presents a review of chemistry terms, definitions, and concepts. All will enhance the reader's foundational understanding of the material presented.

10.2 CHEMISTRY CONCEPTS AND DEFINITIONS

Chemistry has its own language; thus, to understand chemistry, you must understand the following concepts and key terms.

10.2.1 Concepts

1. Concepts: Miscible, Solubility, In Solution, Dissolved
   a. Miscible means capable of being mixed in all proportions. Simply stated, when two or more substances disperse themselves uniformly in all proportions when brought into contact, they are said to be completely soluble in one another, or completely miscible. The precise chemistry definition is: "homogenous molecular dispersion of two or more substances."[2] Examples are:
      i. All gases are completely miscible.
      ii. Water and alcohol are completely miscible.
      iii. Water and mercury (in its liquid form) are immiscible liquids.
   b. Between the two extremes of miscibility, there is a range of solubility — various substances

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mix with one another up to a certain proportion. In many environmental situations, a rather small amount of contaminant is soluble in water in contrast to complete miscibility of water and alcohol. The amounts are measured in parts per million.

2. Concepts: Suspension, Sediment, Particles, Solids
   a. Often water carries solids or particles in suspension. These dispersed particles are much larger than molecules and may be comprised of millions of molecules. The particles may be suspended in flowing conditions and initially under quiescent conditions, but eventually gravity causes settling of the particles. The resultant accumulation by settling is often called sediment or biosolids (sludge) or residual solids in wastewater treatment vessels. Between this extreme of readily falling out by gravity and permanent dispersal as a solution at the molecular level, there are intermediate types of dispersion or suspension. Particles can be so finely milled or of such small intrinsic size as to remain in suspension almost indefinitely and in some respects similarly to solutions.
3. Concept: Emulsion
   a. Emulsions represent a special case of a suspension. As you know, oil and water do not mix. Oil and other hydrocarbons derived from petroleum generally float on water with negligible solubility in water. In many instances, oils may be dispersed as fine oil droplets (an emulsion) in water and not readily separated by floating because of size and/or the addition of dispersal promoting additives. Oil and, in particular, emulsions can prove detrimental to many treatment technologies and must be treated in the early steps of a multistep treatment train.
4. Concept: Ion
   a. An ion is an electrically charged particle. For example, sodium chloride or table salt forms charged particles on dissolution in water; sodium is positively charged (a cation), and chloride is negatively charged (an anion). Many salts similarly form cations and anions on dissolution in water.
5. Concept: Mass Concentration
   a. Concentration is often expressed in terms of parts per million (ppm) or mg/L. Sometimes parts per thousand (ppt) or parts per billion (ppb) are also used.

charged hydronium ion. This process is com-

$$ppm = \frac{\text{Mass of Substance}}{\textit{Mass of Solutions}} \tag{10.1}$$

Because 1 kg of solution with water as a solvent has a volume of approximately 1 L,

$$1 \text{ ppm} \approx 1 \text{ mg/L}$$

10.2.2 Definitions

Anion a negative charged ion.

Atom the smallest particle of an element that can unite chemically with other elements. All the atoms of an element are the same in chemical behavior, although they may differ slightly in weight. Most atoms can combine chemically with other atoms to form molecules.

Cation a positive charged ion.

Chemistry the science that deals with the composition and changes in composition of substances. Water is an example of this composition; it is composed of two gases, hydrogen and oxygen. Water also changes form from liquid to solid to gas, but does not necessarily change composition.

Colloidal any substance in a certain state of fine division in which the particles are less than one μm in diameter.

Compound a substance of two or more chemical elements chemically combined. Examples include water (H_2O), which is a compound formed by hydrogen and oxygen, and carbon dioxide (CO_2), which is composed of carbon and oxygen.

Dissolved solids the material in water that will pass through a glass fiber filter and remain in an evaporating dish after evaporation of the water.

Element the simplest form of chemical matter. Each element has chemical and physical characteristics different from all other kinds of matter.

Gases of neither definite volume nor shape, they completely fill any container in which they are placed.

Inorganic chemical substances of mineral origin.

Ion an atom or group of atoms that carries a positive or negative electric charge as a result of having lost or gained one or more electrons.

Ionization the formation of ions by splitting of molecules or electrolytes in solution. Water molecules are in continuous motion, even at lower temperatures. When two water molecules collide, a hydrogen ion is transferred from one molecule to the other. The water molecule that loses the hydrogen ion becomes a negatively charged hydroxide ion. The water molecule that gains the hydrogen ion becomes a positively monly referred to as the self-ionization of water.

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Coarse	Fine	Colloidal	Molecular
1000 nm	100 nm	1 nm	

FIGURE 10.1 Size ranges of solids. (Adapted from Sawyer, C.N., McCarty, P.L., and Parkin, G.F., *Chemistry for Environmental Engineering,* 4th ed., McGraw-Hill, Toronto, 1994.

Liquids a definite volume, but not shape, liquid will fill containers to certain levels and form free level surfaces.

Matter anything that has weight (mass) and occupies space. Types of matter include elements, compounds, and mixtures.

Mixture a physical, not chemical, intermingling of two of more substances. Sand and salt stirred together form a mixture.

Molecule the smallest particle of matter or a compound that possesses the same composition and characteristics as the rest of the substance. A molecule may consist of a single atom, two or more atoms of the same kind, or two or more atoms of different kinds.

Organic chemical substances of animal or vegetable origin made of carbon structure.

Precipitate a solid substance that can be dissolved, but is separated from solution because of a chemical reaction or change in conditions such as pH or temperature.

Radical two or more atoms that unite in a solution and behave chemically as if a single atom.

Saturated solution the physical state in which a solution will no longer dissolve more of the dissolving substance — solute.

Solids substances that maintain definite size and shape. Solids in water fall into one of the following categories: dissolved, colloidal, and suspended.

1. Dissolved solids are in solution and pass through a filter. The solution consisting of the dissolved components and water forms a single phase, (a homogenous solution).
2. Colloidal solids (sols) are uniformly dispersed in solution but they form a solid phase that is distinct from the water phase.
3. Suspended solids are also a separate phase from the solution. Some suspended solids are classified as settleable solids. Placing a sample in a cylinder and measuring the amount of solids that have settled after a set amount of time determine settleable solids. The size of solids increases going from dissolved solids to suspended solids (see Figure 10.1).

Solute the component of a solution that is dissolved by the solvent.

Solvent the component of a solution that does the dissolving.

Suspended solids the quantity of material deposited when a quantity of water, sewage, or other liquid is filtered through a glass fiber filter.

Total solids the solids in water, sewage, or other liquids; it includes the suspended solids (largely removable by a filter) and filterable solids (those which pass through the filter).

Turbidity a condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light rays.

10.3 WATER CHEMISTRY FUNDAMENTALS

Whenever water and wastewater operators add a substance to another substance (from adding sugar to a cup of tea to adding chlorine to water to make it safe to drink), they perform chemistry. These operators (as well as many others) are chemists because they are working with chemical substances, and how those substances react is important for them to know.

10.3.1 MATTER

Going through a day without coming in contact with many kinds of matter would be impossible. Paper, coffee, gasoline, chlorine, rocks, animals, plants, water and air — all the materials of which the world is made — are all different forms or kinds of matter. Earlier we defined matter as anything that has mass (weight) and occupies space — matter is distinguishable from empty space by its presence. Therefore, going through a day without coming into contact with matter is not only correct, but avoiding some form of matter is virtually impossible. Not all matter is the same, even though we narrowly classify all matter into three groups: solids, liquids, and gases. These three groups are called the physical states of matter and are distinguishable from one another by means of two general features, shape and volume.

Note: Mass is closely related to the concept of weight. On Earth, the weight of matter is a measure of the force with which it is pulled by gravity toward the Earth's center. As we leave Earth's surface, the gravitational pull decreases, eventually becoming virtually insignificant, while

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the weight of matter accordingly reduces to zero. Yet, the matter still possesses the same amount of "mass." Hence, the mass and weight of matter are proportional to each other.

Note: Since matter occupies space, a given form of matter is also associated with a definite volume. Space should not be confused with air, since air is itself a form of matter. Volume refers to the actual amount of space that a given form of matter occupies.

Solids have a definite, rigid shape with their particles closely packed together and sticking firmly to each other. A solid does not change its shape to fit a container. Put a solid on the ground and it will keep its shape and volume — it will never spontaneously assume a different shape. Solids also possess a definite volume at a given temperature and pressure.

Liquids maintain a constant volume, but change shape to fit the shape of their container; they do not possess a characteristic shape. The particles of the liquid move freely over one another, but still stick together enough to maintain a constant volume. Consider a glass of water. The liquid water takes the shape of the glass up to the level it occupies. If we pour the water into a drinking glass, the water takes the shape of the glass; if we pour it into a bowl, the water takes the shape of the bowl. If space is available, any liquid assumes whatever shape its container possesses.

Like solids, liquids possess a definite volume at a given temperature and pressure. They tend to maintain this volume when they are exposed to a change in either of these conditions.

Gases have no definite fixed shape and their volume can be expanded or compressed to fill different sizes of containers. A gas or mixture of gases like air can be put into a balloon, and will take the shape of the balloon. Particles of gases do not stick together at all and move about freely, filling containers of any shape and size.

A gas is also identified by its lack of a characteristic volume. When confined to a container with nonrigid, flexible walls, for example, the volume that a confined gas occupies depends on its temperature and pressure. When confined to a container with rigid walls, however, the volume of the gas is forced to remain constant.

Internal linkages among its units, including between one atom and another, maintain the constant composition associated with a given substance. These linkages are called chemical bonds. When a particular process occurs that involves the making and breaking of these bonds, we say that a chemical reaction or a chemical change has occurred.

Chemical changes occur when new substances are formed that have entirely different properties and characteristics. When wood burns or iron rusts, a chemical change has occurred; the linkages — the chemical bonds — are broken.

Physical changes occur when matter changes its physical properties, such as size, shape, and density, as well as when it changes its state (i.e., from gas to liquid to solid). When ice melts or when a glass window breaks into pieces, a physical change has occurred.

10.3.1.1 The Content of Matter: The Elements

Matter is composed of pure basic substances. Earth is made up of the fundamental substances of which all matter is composed. These substances that resist attempts to decompose them into simpler forms of matter are called elements. To date, there are more than 100 known elements. They range from simple, lightweight elements to very complex, heavyweight elements. Some of these elements exist in nature in pure form; others are combined. The smallest unit of an element is the atom.

The simplest atom possible consists of a nucleus having a single proton with a single electron traveling around it. This is an atom of hydrogen, which has an atomic weight of one because of the single proton. The atomic weight of an element is equal to the total number of protons and neutrons in the nucleus of an atom of an element.

In order to gain an understanding of basic atomic structure and related chemical principles, it is useful to compare the atom to our solar system. In our solar system, the sun is the center of everything. The nucleus is the center in the atom. The sun has several planets orbiting around it. The atom has electrons orbiting about the nucleus. It is interesting to note that the astrophysicist, who would likely find this analogy overly simplistic, is concerned mostly with activity within the nucleus. This is not the case with the chemist. The chemist deals principally with the activity of the planetary electrons; chemical reactions between atoms or molecules involve only electrons, with no changes in the nuclei.

The nucleus is made up of positive electrically charged protons and neutrons that are neutral (no charge). The negatively charged electrons orbiting it balance the positive charge in the nucleus. An electron has negligible mass (less than 0.02% of the mass of a proton) that makes it practical to consider the weight of the atom as the weight of the nucleus.

Atoms are identified by name, atomic number, and atomic weight. The atomic number or proton number is the number of protons in the nucleus of an atom. It is equal to the positive charge on the nucleus. In a neutral atom, it is also equal to the number of electrons surrounding the nucleus. As stated previously, the atomic weight of an atom depends on the number of protons and neutrons in the nucleus, the electrons having negligible mass. Atoms (elements) received their names and symbols in

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interesting ways. The discoverer of the element usually proposes a name for it. Some elements get their symbols from languages other than English. The following are common elements with their common names and the names from which the symbol is derived.

Element	Symbol
Chlorine	Cl
Copper	Cu (*Cuprum* — Latin)
Hydrogen	H
Iron	Fe (*Ferrum* — Latin)
Nitrogen	N
Oxygen	O
Phosphorus	P
Sodium	Na (*Natrium* — Latin)
Sulfur	S

As shown above, a capital letter or a capital letter and a small letter designate each element. These are called chemical symbols. As is apparent from the above table, most of the time the symbol is easily recognized as an abbreviation of the atom name, such as O for oxygen.

Typically we do not find most of the elements as single atoms. They are more often found in combinations of atoms called molecules. Basically, a molecule is the least common denominator of making a substance what it is.

A system of formulae has been devised to show how atoms are combined into molecules.

When a chemist writes the symbol for an element, it stands for one atom of the element. A subscript following the symbol indicates the number of atoms in the molecule. O_2 is the chemical formula for an oxygen molecule. It shows that oxygen occurs in molecules consisting of two oxygen atoms. As you know, a molecule of water contains two hydrogen atoms and one oxygen atom, so the formula is H_2O.

Note: The chemical formula of the water molecule, H_2O, was defined in 1860 by the Italian scientist Stanisloa Cannizzarro.

Some elements have similar chemical properties. For example, a chemical such as bromine (atomic number 35) has chemical properties that are similar to the chemical properties of the element chlorine (atomic number 17, which most water and wastewater operators are familiar with) and iodine (atomic number 53).

In 1865, English chemist John Newlands arranged some of the known elements in an increasing order of atomic weights. Newlands' arrangement had the lightest element he knew about at the top of his list and the heaviest element at the bottom. Newlands was surprised when he observed that starting from a given element, every eighth element repeated the properties of the given element.

Later, in 1869, Dmitri Mendeleev, a Russian chemist, published a table of the 63 known elements. In his table, Mendeleev, like Newlands, arranged the elements in an increasing order of atomic weights. He also grouped them in 8 vertical columns so that the elements with similar chemical properties would be found in 1 column. It is interesting to note that Mendeleev left blanks in his table. He correctly hypothesized that undiscovered elements existed that would fill in the blanks when they were discovered. Because he knew the chemical properties of the elements above and below the blanks in his table, he was able to predict quite accurately the properties of some of the undiscovered elements.

Today our modern form of the periodic table is based on work done by the English scientist Henry Moseley, who was killed during World War I. Following the work of Ernest Rutherford (a New Zealand physicist) and Niels Bohr (a Danish physicist), Moseley used x-ray methods to determine the number of protons in the nucleus of an atom.

The atomic number, or number of protons, of an atom is related to its atomic structure. In turn, atomic structure governs chemical properties. The atomic number of an element is more directly related to its chemical properties than its atomic weight. It is more logical to arrange the periodic table according to atomic numbers than atomic weights. By demonstrating the atomic numbers of elements, Moseley enabled chemists to make a better periodic table.

In the periodic table, each box or section contains the atomic number, symbol, and atomic weight of an element. The numbers down the left side of the box show the arrangement, or configuration, of the electrons in the various shells around the nucleus. For example, the element carbon has an atomic number of 6, its symbol is C, and its atomic weight is 12.011 (see Figure 10.2).

In the periodic table, a horizontal row of boxes is called a period or series. Hydrogen is all by itself because of its special chemical properties. Helium is the only element in the first period. The second period contains lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, and neon. Other elements may be identified by looking at the table.

A vertical column is called a group or family. Elements in a group have similar chemical properties.

Atomic weight	**12.01**
Symbol	**C**
Name	**Carbon**
Atomic number	**6**

FIGURE 10.2 Periodic table entry for carbon.

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The periodic table is useful because by knowing where an element is located in the table, you can have a general idea of its chemical properties.

As mentioned, for convenience, elements have specific names and symbols, but are often identified by chemical symbol only. The symbols of the elements consist of either one or two letters, with the first letter capitalized.

We list the elements important to water and wastewater operators (about a third of the 106 elements) below. Those elements most closely associated with water and wastewater treatment are marked with an asterisk.

Element	Symbol	Element	Symbol
Aluminum*	Al	Iron*	Fe
Arsenic	As	Lead	Pb
Barium	Ba	Magnesium*	Mg
Cadmium	Ca	Manganese*	Mn
Carbon*	C	Mercury	Hg
Calcium	Ca	Nitrogen*	N
Chlorine*	Cl	Nickel	Ni
Chromium	Cr	Oxygen*	O
Cobalt	Co	Phosphorus	P
Copper	Cu	Potassium	K
Fluoride*	F	Silver	Ag
Helium	He	Sodium*	Na
Hydrogen*	H	Sulfur*	S
Iodine	I	Zinc	Zn

10.3.2 Compound Substances

If we take a pure substance like calcium carbonate (limestone) and heat it, the calcium carbonate ultimately crumbles to a white powder. However, careful examination of the heating process shows that carbon dioxide also evolves from the calcium carbonate. Substances like calcium carbonate that can be broken down into two or more simpler substances are called *compound substances* or simply *compounds*. Heating is a common way of decomposing compounds, but other forms of energy are often used as well.

Chemical elements that make up compounds such as calcium carbonate combine with each other in definite proportions. When atoms of two or more elements are bonded together to form a compound, the resulting particle is called a molecule.

Note: This law simply means that only a certain number of atoms or radicals of one element will combine with a certain number of atoms or radicals of a different element to form a chemical compound.

Water, (H_2O) is a compound. As stated, compounds are chemical substances made up of two or more elements bonded together. Unlike elements, compounds can be separated into simpler substances by chemical changes. Most forms of matter in nature are composed of combinations of the 100+ pure elements.

If you have a particle of a compound, for example a crystal of salt (sodium chloride), and subdivide until you get the smallest unit of sodium chloride possible, you would have a molecule. As stated, a molecule (or least common denominator) is the smallest particle of a compound that still has the characteristics of that compound.

Note: Because the weights of atoms and molecules are relative and the units are extremely small, chemists works with units they identify as moles. A mole (symbol mol) is defined as the amount of a substance that contains as many elementary entities (atoms, molecules, and so on) as there are atoms in 12 g of the isotope carbon-12.

Note: An isotope of an element is an atom having the same structure as the element — the same electrons orbiting the nucleus, and the same protons in the nucleus, but having more or fewer neutrons.

One mole of an element that exists as a single atom weighs as many grams as its atomic number (so 1 mole of carbon weighs 12 g), and it contains 6.022045×10^{23} atoms, which is Avogadro's number.

As stated previously, symbols are used to identify elements. This is a shorthand method for writing the names of the elements. This shorthand method is also used for writing the names of compounds. Symbols used in this manner show the kinds and numbers of different elements in the compound. These shorthand representations of chemical compounds are called chemical formulas. For example, the formula for table salt (sodium chloride) is NaCl. The formula shows that one atom of sodium combines with one atom of chlorine to form sodium chloride. Let's look at a more complex formula for the compound sodium carbonate (soda ash): Na_2CO_3. The formula shows that this compound is made up of three elements: sodium, carbon, and oxygen. In addition, there are two atoms of sodium, one atom of carbon, and three atoms of oxygen in each molecule.

As mentioned, when depicting chemical reactions, chemical equations are used. The following equation shows a chemical reaction that most water and wastewater operators are familiar with: chlorine gas added to water. It shows the formulas of the molecules that react together and the formulas of the product molecules.

$$Cl_2 + H_2O \rightarrow HOCl + HCl$$

As stated previously, a chemical equation tells what elements and compounds are present before and after a chemical reaction. Sulfuric acid poured over zinc will

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cause the release of hydrogen and the formation of zinc sulfate. This is shown by the following equation:

$$Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2$$

One atom (also one molecule) of zinc unites with one molecule sulfuric acid giving one molecule of zinc sulfate and one molecule (two atoms) of hydrogen. Notice that there is the same number of atoms of each element on each side of the arrow. However, the atoms are combined differently.

Let us look at another example.

When hydrogen gas is burned in air, the oxygen from the air unites with the hydrogen and forms water. The water is the product of burning hydrogen. This can be expressed as an equation.

$$2H_2 + O_2 \rightarrow 2H_2O$$

This equation indicates that two molecules of hydrogen unite with one molecule of oxygen to form two molecules of water.

10.4 THE WATER MOLECULE

Now that we have introduced a few important fundamentals of chemistry, we turn our attention to the key player in this text: the water molecule.

Just about every high school-level student knows that water is a chemical compound of two simple and abundant elements, yet scientists continue to argue the merits of rival theories on the structure of water. The fact is we still understand little about water. For example, we do not know much about how water works.

Part of the problem lies with the fact that no one has ever seen a water molecule. While we have theoretical diagrams and equations, and we have a disarmingly simple formula — H_2O — the reality is that water is very complex. X-rays, for example, have shown that the atoms in water are intricately laced.

Water is different from any other substance we know. Consider the water molecule, for example, where the two hydrogen atoms always come to rest at an angle of approximately 105° from each other, making all diagrams of their attachment to the larger oxygen atom look sort of like an on-its-side set of Mickey Mouse ears on a very round head. The hydrogens tend to be positively charged and the oxygen tends to be negatively charged. This gives the water molecule an electrical polarity; one end positively charged and one end negatively charged.

In short, this 105° relationship makes water lopsided, peculiar, and eccentric — it breaks all the rules (see Figure 10.3).

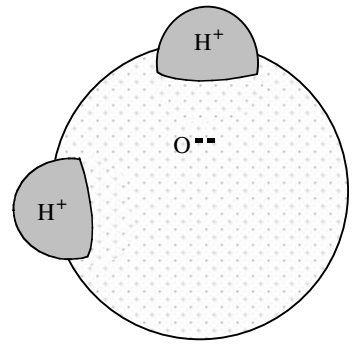

FIGURE 10.3 A molecule of water. (From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.)

In the laboratory, pure water contains no impurities, but in nature, water contains many things besides water. Water is a very good solvent (in fact, water is known as the universal solvent). The polarity just described is the main reason water is able to dissolve so many other substances. For the water operator tasked with making water as pure as possible, this fact makes the job more difficult. Water contains many dissolved and suspended elements and particles — and the waterworks operator must deal with them.

10.5 WATER SOLUTIONS

A solution is a condition in which one or more substances are uniformly and evenly mixed or dissolved. A solution has two components, a solvent and a solute. The solvent is the component that does the dissolving. The solute is the component that is dissolved. In water solutions, water is the solvent. Water can dissolve many other substances — given enough time, there are not too many solids, liquids, and gases that water cannot dissolve. When water dissolves substances, it creates solutions with many impurities.

Generally, a solution is usually transparent and not cloudy. However, a solution may be colored when the solute remains uniformly distributed throughout the solution and does not settle with time.

When molecules dissolve in water, the atoms making up the molecules come apart (dissociate) in the water. This dissociation in water is called ionization. When the atoms in the molecules come apart, they do so as charged atoms (both negatively and positively charged) called ions. As mentioned, the positively charged ions are called cations and the negatively charged ions are called anions.

A good example of the ionization occurs when calcium carbonate ionizes:

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$$\underset{\text{calcium carbonate}}{CaCO_3} \leftrightarrow \underset{\substack{\text{calcium ion}\\(\text{cation})}}{Ca^{++}} + \underset{\substack{\text{carbonate ion}\\(\text{anion})}}{CO_3^{-2}}$$

Another good example is the ionization that occurs when table salt (sodium chloride) dissolves in water:

$$\underset{\text{sodium chloride}}{NaCl} \leftrightarrow \underset{\substack{\text{sodium ion}\\(\text{cation})}}{Na^{+}} + \underset{\substack{\text{chloride ion}\\(\text{anion})}}{CL^{-}}$$

Some of the common ions found in water are listed as follows:

Ion	Symbol
Hydrogen	H^+
Sodium	Na^+
Potassium	K^+
Chloride	Cl^-
Bromide	Br^-
Iodide	I^-
Bicarbonate	HCO_3^-

Water dissolves polar substances better than nonpolar substances. This makes sense when you consider that water is a polar substance. Polar substances, such as mineral acids, bases, and salts, are easily dissolved in water. Nonpolar substances, such as oils, fats and many organic compounds, do not dissolve easily in water.

Water dissolves polar substances better than nonpolar substances — only to a point. Polar substances dissolve in water up to a point — only so much solute will dissolve at a given temperature, for example. When that limit is reached, the resulting solution is saturated. When a solution becomes saturated, no more solute can be dissolved. For solids dissolved in water, if the temperature of the solution is increased, the amount of solids (solutes) required to reach saturation increases.

10.6 WATER CONSTITUENTS

Natural water can contain a number of substances (what we may call impurities) or constituents in water and wastewater operations. The concentrations of various substances in water in dissolved, colloidal, or suspended form are typically low but vary considerably. A hardness value of up to 400 ppm of calcium carbonate, for example, is sometimes tolerated in public supplies, whereas 1 ppm of dissolved iron would be unacceptable.

When a particular constituent can affect the good health of the water user or the environment, it is called a contaminant or pollutant. These contaminants are what the water and wastewater operator works to prevent from the water supply or removes from the wastestream. In this section, we discuss some of the more common constituents of water.

10.6.1 Solids

Other than gases, all contaminants of water contribute to the solids content. Natural water carries many dissolved and undissolved solids. The undissolved solids are nonpolar substances and consist of relatively large particles of materials such as silt, that will not dissolve. Classified by their size and state, chemical characteristics, and size distribution, solids can be dispersed in water in both suspended and dissolved forms.

Size of solids in water can be classified as suspended solids, settleable, colloidal, or dissolved. Total solids are those suspended and dissolved solids that remain behind when the water is removed by evaporation. Solids are also characterized as being volatile or nonvolatile.

The distribution of solids is determined by computing the percentage of filterable solids by size range. Solids typically include inorganic solids, such as silt and clay from riverbanks, and organic matter, such as plant fibers and microorganisms from natural or man-made sources.

Note: Though not technically accurate from a chemical point of view because some finely suspended material can actually pass through the filter, suspended solids are defined as those that can be filtered out in the suspended solids laboratory test. The material that passes through the filter is defined as dissolved solids.

As mentioned, colloidal solids are extremely fine suspended solids (particles) of less than one μm in diameter; they are so small (though they still make water cloudy) that they will not settle even if allowed to sit quietly for days or weeks.

10.6.2 Turbidity

Simply, turbidity refers to how clear the water is. Water's clarity is one of the first characteristics people notice. Turbidity in water is caused by the presence of suspended matter, resulting in the scattering and absorption of light rays. The greater the amount of total suspended solids in the water, the murkier it appears and the higher the measured turbidity. Thus, in plain English, turbidity is a measure of the light-transmitting properties of water. Natural water that is very clear (low turbidity) allows you to see images at considerable depths, while high turbidity water appears cloudy. Keep in mind that water of low turbidity is not necessarily without dissolved solids. Dissolved solids do not cause light to be scattered or absorbed, making the water look clear. High turbidity causes problems for the waterworks operator — components that cause high tur-

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bidity can cause taste and odor problems and will reduce the effectiveness of disinfection.

10.6.3 Color

Color in water can be caused by a number of contaminants, such as iron, which changes in the presence of oxygen to yellow or red sediments. The color of water can be deceiving. In the first place, color is considered an aesthetic quality of water with no direct health impact. Secondly, many of the colors associated with water are not true colors, but the result of colloidal suspension (apparent color). This apparent color can often be attributed to iron and to dissolved tannin extracted from decaying plant material. True color is the result of dissolved chemicals (most often organics) that cannot be seen. True color is distinguished from apparent color by filtering the sample.

10.6.4 Dissolved Oxygen

Gases can also be dissolved in water. Oxygen, carbon dioxide, hydrogen sulfide, and nitrogen are examples of gases that dissolve in water. Gases dissolved in water are important. For example, carbon dioxide is important because of the role it plays in pH and alkalinity. Carbon dioxide is released into the water by microorganisms and consumed by aquatic plants. However, dissolved oxygen (DO) in water is of most importance to us here. DO is not only important to most aquatic organisms, but it is also an important indicator of water quality.

Like terrestrial life, aquatic organisms need oxygen to live. As water moves past their breathing apparatus, microscopic bubbles of oxygen gas in the water, DO, are transferred from the water to their blood. Like any other gas diffusion process, the transfer is efficient only above certain concentrations. In other words, oxygen can be present in the water, but at too low a concentration to sustain aquatic life. Oxygen also is needed by virtually all algae and macrophytes, and for many chemical reactions that are important to water body functioning.

Note: As mentioned, solutions can become saturated with solute. This is the case with water and oxygen. As with other solutes, the amount of oxygen that can be dissolved at saturation depends upon the temperature of the water. In the case of oxygen, the effect is just the opposite of other solutes. The higher the temperature, the lower the saturation level; the lower the temperature, the higher the saturation level.

10.6.5 Metals

Metals are elements that are present in chemical compounds as positive ions, or in the form of cations (+ ions) in solution. Metals with a density over 5 kg/dm^3 are known as *heavy metals.* Metals are one of the constituents or impurities often carried by water. Although most of the metals are not harmful at normal levels, a few metals can cause taste and odor problems in drinking water. In addition, some metals may be toxic to humans, animals and microorganisms. Most metals enter water as part of compounds that ionize to release the metal as positive ions.

Table 10.1 lists some metals commonly found in water and their potential health hazards.

TABLE 10.1
Common Metals Found in Water

Metal	Health Hazard
Barium	Circulatory system effects and increased blood pressure
Cadmium	Concentration in the liver, kidneys, pancreas, and thyroid
Copper	Nervous system damage and kidney effects; toxic to humans
Lead	Nervous system damage and kidney effects; toxic to humans
Mercury	Central nervous system disorders
Nickel	Central nervous system disorders
Selenium	Central nervous system disorders
Silver	Turns skin gray
Zinc	Causes taste problems (not a health hazard)

Source: From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

Note: Metals may be found in various chemical and physical forms. These forms, or "species," can be particles or simple organic compounds, organic complexes or colloids. The dominating form is determined largely by the chemical composition of the water, the matrix, and in particular the pH.

10.6.6 Organic Matter

Organic matter or compounds are those that contain the element carbon and are derived from material that was once alive (i.e., plants and animals). Organic compounds include fats, dyes, soaps, rubber products, plastics, wood, fuels, cotton, proteins, and carbohydrates. Organic compounds in water are usually large, nonpolar molecules that do not dissolve well in water. They often provide large amounts of energy to animals and microorganisms.

Note: Natural organic matter (NOM) is used to describe the complex mixture of organic material, such as humic and hydrophilic acids, present in all drinking water sources. NOM can cause major problems in the treatment of water as it reacts with chlorine to form disinfection by-products (DBPs). Many of the disinfection DBPs formed by the reaction of NOM with

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disinfectants are reported to be toxic and carcinogenic to humans if ingested over an extended period. The removal of NOM and reduction in DBPs is a major goal in the treatment of any water source. We discuss NOM and DBPs in detail later.

10.6.7 Inorganic Matter

Inorganic matter or compounds are carbon-free, not derived from living matter, and easily dissolved in water; they are of mineral origin. The inorganics include acids, bases, oxides, salts, etc. Several inorganic components are important in establishing and controlling water quality. Two important inorganic constituents in water are nitrogen and phosphorous.

10.6.7.1 Acids

Lemon juice, vinegar, and sour milk are acidic or contain acid. The common acids used in waterworks operations are hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3) and carbonic acid (H_2CO_3). Note that in each of these acids, hydrogen (H) is one of the elements.

Note: An acid is a substance that produces hydrogen ions (H^+) when dissolved in water. Hydrogen ions are hydrogen atoms stripped of their electrons. A single hydrogen ion is nothing more than the nucleus of a hydrogen atom.

The relative strengths of acids in water (listed in descending order of strength) are classified in Table 10.2.

Note: Acids and bases become solvated — they loosely bond to water molecules.

TABLE 10.2
Relative Strengths of Acids in Water

Acid	Symbol
Perchloric acid	$HClO_4$
Sulfuric acid	H_2SO_4
Hydrochloric acid	HCl
Nitric acid	HNO_3
Phosphoric acid	H_3PO_4
Nitrous acid	HNO_2
Hydrofluoric acid	HF
Acetic acid	CH_3COOH
Carbonic acid	H_2CO_3
Hydrocyanic acid	HCN
Boric acid	H_3BO_3

Source: From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

10.6.7.2 Bases

A *base* is a substance that produces hydroxide ions (OH^-) when dissolved in water. Lye or common soap (bitter things) contains bases. The bases used in waterworks operations are calcium hydroxide ($Ca\ [OH]_2$), sodium hydroxide (NaOH), and potassium hydroxide (KOH). Note that the hydroxyl group (OH) is found in all bases. In addition, note that bases contain metallic substances, such as sodium, calcium, magnesium, and potassium. These bases contain the elements that produce the alkalinity in water.

10.6.7.3 Salts

When acids and bases chemically interact, they neutralize each other. The compound (other than water) that forms from the neutralization of acids and bases is called a *salt*. Salts constitute, by far, the largest group of inorganic compounds. A common salt used in waterworks operations, copper sulfate, is utilized to kill algae in water.

10.7 pH

pH is a measure of the hydrogen ion (H^+) concentration. Solutions range from very acidic (having a high concentration of H^+ ions) to very basic (having a high concentration of OH^- ions). The pH scale ranges from 0 to 14, with 7 being the neutral value (see Figure 10.4). The pH of water is important to the chemical reactions that take place within water, and pH values that are too high or low can inhibit the growth of microorganisms.

With high and low pH values, high pH values are considered basic and low pH values are considered acidic. Stated another way, low pH values indicate a high level of H^+ concentration, while high pH values indicate a low H^+ concentration. Because of this inverse logarithmic relationship, there is a tenfold difference in H^+ concentration.

Natural water varies in pH depending on its source. Pure water has a neutral pH, with an equal number H^+ and OH^-. Adding an acid to water causes additional positive ions to be released, so that the H^+ ion concentration goes up and the pH value goes down.

$$HCl \leftrightarrow H^+ + Cl^-$$

To control water coagulation and corrosion, the waterworks operator must test for the hydrogen ion concentration of the water to determine the water's pH. In a coagulation test, as more alum (acid) is added, the pH value lowers. If more lime (alkali) is added, the pH value rises. This relationship should be remembered — if a good floc is formed, the pH should then be determined and maintained at that pH value until the raw water changes.

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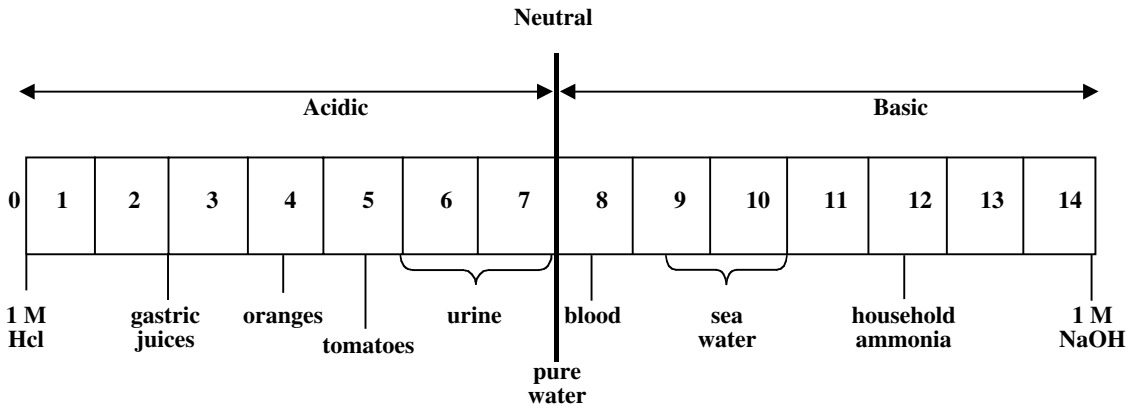

FIGURE 10.4 pH of selected liquids. (From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.)

10.8 ALKALINITY

Alkalinity is defined as the capacity of water to accept protons; it can also be defined as a measure of water's ability to neutralize an acid. Bicarbonates, carbonates, and hydrogen cause alkalinity and hydrogen compounds in a raw or treated water supply. Bicarbonates are the major components because of carbon dioxide action on basic materials of soil; borates, silicates, and phosphates may be minor components. Alkalinity of raw water may also contain salts formed from organic acids such as humic acids.

Alkalinity in water acts as a buffer that tends to stabilize and prevent fluctuations in pH. In fact, alkalinity is closely related to pH, but the two must not be confused. Total alkalinity is a measure of the amount of alkaline materials in the water. The alkaline materials act as the buffer to changes in the pH. If the alkalinity to too low (below 80 ppm) there can be rapid fluctuations in pH (i.e., there is insufficient buffer to the pH). High alkalinity (above 200 ppm) results in the water being too buffered. Thus, having significant alkalinity in water is usually beneficial, because it tends to prevent quick changes in pH that interfere with the effectiveness of common water treatment processes. Low alkalinity also contributes to water's corrosive tendencies.

Note: When alkalinity is below 80 mg/L, it is considered low.

10.9 HARDNESS

Hardness may be considered a physical or chemical characteristic or parameter of water. It represents the total concentration of calcium and magnesium ions, reported as calcium carbonate. Hardness causes soaps and detergents to be less effective and contributes to scale formation in pipes and boilers. Hardness is not considered a health hazard; however, water that contains hardness must often be softened by lime precipitation or ion exchange. Low hardness contributes to the corrosive tendencies of water. Hardness and alkalinity often occur together, because some compounds can contribute both alkalinity and hardness ions. Hardness is generally classified as shown in Table 10.3.

TABLE 10.3
Water Hardness

Classification	mg/L $CaCo_3$
Soft	0–75
Moderately hard	75–150
Hard	150–300
Very hard	Over 300

Source: From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

10.10 WATER AND WASTEWATER CHEMICALS AND CHEMICAL PROCESSES

In order to operate a water/wastewater treatment process correctly and safely, water/wastewater operators need to know the types of chemical used in the processes, what the purpose of each is, and the safety precautions required in the use of each. This section briefly discusses chemicals used in the following:

1. Odor control (wastewater treatment)
2. Disinfection
3. Chemical precipitation
4. Adsorption
5. Coagulation
6. Taste and odor removal (water treatment)
7. Water softening
8. Recarbonation
9. Ion exchange softening
10. Scale and corrosion control

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10.10.1 Odor Control (Wastewater Treatment)

There is an old saying in wastewater treatment: "Odor is not a problem until the neighbors complain."[3] Experience has shown that when treatment plant odor is apparent, it is not long before the neighbors do complain. Thus, odor control is an important factor affecting the performance of any wastewater treatment plant, especially in regards to public relations.

According to Metcalf & Eddy, Inc., in wastewater operations,

> The principal sources of odors are from (1) septic wastewater containing hydrogen sulfide and odorous compounds, (2) industrial wastes discharged into the collection system, (3) screenings and unwanted grit, (4) septage handling facilities, (5) scum on primary settling tanks, (6) organically overloaded treatment processes, (7) [biosolids]-thickening tanks, (8) waste gas-burning operations where lower-than optimum temperatures are used, (9) [biosolids]-conditioning and dewatering faculties, (10) [biosolids] incineration, (11) digested [biosolids] in drying beds or [biosolids]-holding basins, and (12) [biosolids]-composting operations.[4]

Odor control can be accomplished by chemical or physical means. Physical means include utilizing buffer zones between the process operation and the public, making operation changes, controlling discharges to collection systems, containments, dilution, fresh air, adsorption, using activated carbon, scrubbing towers, and other means.

Odor control by chemical means involves scrubbing with various chemicals, chemical oxidation, and chemical precipitation methods. In scrubbing with chemicals, odorous gases are passed through specially designed scrubbing towers to remove odors. The commonly used chemical scrubbing solutions are chlorine and potassium permanganate. When hydrogen sulfide concentrations are high, sodium hydroxide is often used. In chemical oxidation applications, the oxidants chlorine, ozone, hydrogen peroxide, and potassium permanganate are used to oxidize the odor compounds. Chemical precipitation works to precipitate sulfides from odor compounds using iron and other metallic salts.

10.10.2 Disinfection

In water and wastewater practice, disinfection is often accomplished using chemicals. The purpose of disinfection is to selectively destroy disease-causing organisms. Chemicals commonly used in disinfection include chlorine and its compounds (most widely used), ozone, brome, iodine, hydrogen peroxide, and others.

Note: Considerably more chlorine is required for disinfection of wastewater (40 to 60 g/m^3) than for domestic water supplies (2 to 4 g/m^3).

Many factors must be considered when choosing the type of chemical to be used for disinfection. These factors include: contact time, intensity and nature of the physical agent, temperature, and type and number of organisms.

10.10.3 Chemical Precipitation

In wastewater treatment, chemical precipitation is used to remove phosphorus and to enhance suspended-solids removal in sedimentation processes. The most common chemicals used are aluminum hydroxide (alum), ferric chloride, ferric sulfate, and lime.

10.10.4 Adsorption

In wastewater treatment, adsorption, using granular activated carbon (GAC), is utilized to remove organics not removed and other chemical treatment processes. Adsorption can also be used for the dechlorination of wastewater before final discharge of treated effluent. Typically, adsorption (using GAC) is used on chlorinated water supplies that would not contain pathogenic bacteria, but nonpathogenic bacteria may be present in the water supply and grow on the media.

10.10.5 Coagulation

Chemical coagulation conditions water for further treatment by the removal of:

1. Turbidity, color, and bacteria
2. Iron and manganese
3. Tastes, odors, and organic pollutants

In water treatment, normal sedimentation processes do not always settle out particles efficiently. This is especially the case when attempting to remove particles of less than 50 μm in diameter.

In some instances, it is possible to agglomerate (to make or form into a rounded mass) particles into masses or groups. These rounded masses are of increased size and therefore increased settling velocities, in some instances. For colloidal-sized particles, however, agglomeration is difficult — turbid water resulting from colloidal particles is difficult to clarify without special treatment.

Chemical coagulation is usually accomplished by the addition of metallic salts such as aluminum sulfate (alum) or ferric chloride. Alum is the most commonly used coagulant in water treatment and is most effective between pH ranges of 5.0 and 7.5. Sometimes polymer is added to alum to help form small floc together for faster settling.

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Ferric chloride, effective down to a pH of 4.5 is sometimes used.

In addition to pH, a variety of other factors influence the chemical coagulation process, including

1. Temperature
2. Influent quality
3. Alkalinity
4. Type and amount of coagulant used
5. Type and length of flocculation
6. Type and length of mixing

10.10.6 Taste and Odor Removal

Although odor can be a problem with wastewater treatment, the taste and odor parameter is only associated with potable water. Either organic or inorganic materials may produce tastes and odors in water. The perceptions of taste and odor are closely related and often confused by water practitioners as well as by consumers. It is difficult to precisely measure either one. Experience has shown that a substance that produces an odor in water almost invariably imparts a perception of taste as well. This is not the case. Taste is generally attributed to mineral substances in the water. Most of these minerals affect water taste but do not cause odors.

Along with the impact minerals can have on water taste, there are other substances or practices that can affect both water tastes and odors (e.g., metals, salts from the soil, constituents of wastewater, and end products generated from biological reactions). When water has a distinct taste but no odor, the taste might be the result of inorganic substances. Anyone who has tasted alkaline water has also tasted its biting bitterness. Then there are the salts; they not only give water that salty taste but also contribute to its bitter taste. Other than from natural causes, water can take a distinctive color or taste, or both, from human contamination of the water.

Organic materials can produce both taste and odor in water. Petroleum-based products are probably the prime contributors to both these problems in water.

Biological degradation or decomposition of organics in surface waters also contributes to both taste and odor problems in water. Algae are another problem. Certain species of algae produce oily substances that may result in both taste and odor. Synergy can also work to produce taste and odor problems in water. Mixing water and chlorine is one example.

In regards to chemically treating water for odor and taste problems, oxidants such as chlorine, chlorine dioxide, ozone, and potassium permanganate can be used. These chemicals are especially effective when water is associated with an earthy or musty odor caused by the nonvolatile metabolic products of actinomycetes and blue-green algae. Tastes and odors associated with dissolved gases and some volatile organic materials are normally removed by oxygen in aeration processes.

10.10.7 Water Softening

The reduction of hardness, or softening, is a process commonly practiced in water treatment. Chemical precipitation and ion exchange are the two softening processes that are most commonly used. Softening of hard water is desired (for domestic users) to reduce the amount of soap used, increase the life of water heaters, and to reduce encrustation of pipes (cementing together the individual filter media grains).

In chemical precipitation, it is necessary to adjust pH. To precipitate the two ions most commonly associated with hardness in water, calcium (Ca^{+2}) and magnesium (Mg^{+2}), the pH must be raised to about 9.4 for calcium and about 10.6 for magnesium. To raise the pH to the required levels lime is added.

Chemical precipitation is accomplished by converting calcium hardness to calcium carbonate and magnesium hardness to magnesium hydroxide. This is normally accomplished by using the lime-soda ash or the caustic soda processes.

The lime-soda ash process reduces the total mineral content of the water, removes suspended solids, removes iron and manganese, and reduces color and bacterial numbers. The process has a few disadvantages. McGhee points out, for example, the process produces large quantities of sludge and requires careful operation. In addition, as stated earlier, if the pH is not properly adjusted, it may create operational problems downstream of the process.[5]

In the caustic soda process, the caustic soda reacts with the alkalinity to produce carbonate ions for reduction with calcium. The process works to precipitate calcium carbonate in a fluidized bed of sand grains, steel grit, marble chips, or some other similar dense material. As particles grow in size by deposition of $CaCO_3$, they migrate to the bottom of the fluidized bed from which they are removed. This process has the advantages of requiring short detention times (about 8 seconds) and producing no sludge.

10.10.8 Recarbonation

Recarbonation (stabilization) is the adjustment of the ionic condition of a water so that it will neither corrode pipes nor deposit calcium carbonate, which produces an encrusting film. During or after the lime-soda ash softening process, this recarbonation is accomplished through the reintroduction of carbon dioxide into the water. Lime softening of hard water supersaturates the water with calcium carbonate and may have a pH of greater than 10. Because of this,

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pressurized carbon dioxide is bubbled into the water, lowering the pH and removing calcium carbonate. The high pH can also create a bitter taste in drinking water. Recarbonation removes this bitterness.

10.10.9 Ion Exchange Softening

Hardness can be removed by ion exchange. In water softening, ion exchange replaces calcium and magnesium with a nonhardness cation, usually sodium. Calcium and magnesium in solution are removed by interchange with sodium within a solids interface (matrix) through which the flow is passed. Similar to the filter, the ion exchanger contains a bed of granular material, a flow distributor, and an effluent vessel that collects the product. The exchange media include greensand (a sand or sediment given a dark greenish color by grains of glauconite), aluminum silicates, synthetic siliceous gels, bentonite clay, sulfonated coal, and synthetic organic resins; they are generally in particle form and usually range up to a diameter of 0.5 mm. Modern applications more often employ artificial organic resins. These clear, BB-sized resins are sphere-shaped and have the advantage of providing a greater number of exchange sites. Each of these resin spheres contains sodium ions that are released into the water in exchange for calcium and magnesium. As long as exchange sites are available, the reaction is virtually instantaneous and complete.

When all the exchange sites have been utilized, hardness begins to appear in the influent (breakthrough). When breakthrough occurs, this necessitates the regeneration of the medium by contacting it with a concentrated solution of sodium chloride.

Ion exchange used in water softening has both advantages and disadvantages. One of its major advantages is that it produces a softer water than does chemical precipitation. Additionally, ion exchange does not produce the large quantity of sludge encountered in the lime-soda process. One disadvantage is that although it does not produce sludge, ion exchange does produce concentrated brine. Moreover, the water must be free of turbidity and particulate matter or the resin might function as a filter and become plugged.

10.10.10 Scaling and Corrosion Control

Controlling scale and corrosion is important in water systems. Carbonate and noncarbonate hardness constituents in water cause scale. It forms a chalky-white deposit frequently found on teakettle bottoms. When controlled, this scale can be beneficial, forming a protective coating inside tanks and pipelines. A problem arises when scale is not controlled. Excessive scaling reduces the capacity of pipelines and the efficiency of heat transfer in boilers.

Corrosion is the oxidation of unprotected metal surfaces. Of particular concern, in water treatment, is the corrosion of iron and its alloys (i.e., the formation of rust). Several factors contribute to the corrosion of iron and steel. Alkalinity, pH, DO, and carbon dioxide can all cause corrosion. Along with the corrosion potential of these chemicals, their corrosive tendencies are significantly increased when water temperature and flow are increased.

10.11 CHAPTER REVIEW QUESTIONS AND PROBLEMS

10.1. The chemical symbol for sodium is _____.

10.2. The chemical symbol for sulfuric acid is _____.

10.3. Neutrality on the pH scale is _____.

10.4. Is NaOH a salt or a base?

10.5. Chemistry is the study of substances and the _____ they undergo.

10.6. The three states of matter are _____, _____, and _____.

10.7. A basic substance that cannot be broken down any further without changing the nature of the substance is _____.

10.8. A combination of two or more elements is a _____.

10.9. A table of the basic elements is called the _____ table.

10.10. When a substance is mixed into water to form a solution, the water is called the _____, and the substance is called the _____.

10.11. Define ion.

10.12. A solid that is less than 1 μm in size is called a _____.

10.13. The property of water that causes light to be scattered and absorbed is _____.

10.14. What is true color?

10.15. What is the main problem with metals found in water?

10.16. Compounds derived from material that once was alive are called _____ chemicals.

10.17. pH range is from _____ to _____.

10.18. What is alkalinity?

10.19. The two ions that cause hardness are _____ and _____.

10.20. What type of substance produces hydroxide ions (OH^-) in water?

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11 Water Microbiology

Scientists picture the primordial Earth as a planet washed by a hot sea and bathed in an atmosphere containing water vapor, ammonia, methane, and hydrogen. Testing this theory, Stanley Miller at the University of Chicago duplicated these conditions in the laboratory. He distilled seawater in a special apparatus, passed the vapor with ammonia, methane and hydrogen through an electrical discharge at frequent intervals, and condensed the "rain" to return to the boiling seawater. Within a week, the seawater had turned red. Analysis showed that it contained amino acids, which are the building blocks of protein substances.

Whether this is what really happened early in the Earth's history is not important; the experiment demonstrated that the basic ingredients of life could have been made in some such fashion, setting the stage for life to come into existence in the sea. The saline fluids in most living things may be an inheritance from such early beginnings.[1]

11.1 INTRODUCTION

Microorganisms are significant in water and wastewater because of their roles in disease transmission and in biological treatment processes. Water, wastewater, and other water practitioners must have considerable knowledge of the microbiological characteristics of water and wastewater. Simply put, waterworks operators cannot fully comprehend the principles of effective water treatment without knowing the fundamental factors concerning microorganisms and their relationships to one another; their effect on the treatment process; and their impact on consumers, animals, and the environment.

Water and wastewater operators must know what principal groups of microorganisms are typically found in water supplies (surface and groundwater) and wastewater. They must be able to identify those microorganisms that must be treated (pathogenic organisms) and be removed or controlled for biological treatment processes. They must also be able to identify the organisms used as indicators of pollution/contamination and know their significance, and they must know the methods used to enumerate the indicator organisms. Finally, they must be familiar with those organisms that indicate process conditions to optimize process operation.

Note: In order to have microbiological activity the body of water or wastewater must possess the appropriate environmental conditions. The majority of wastewater treatment processes, for example, are designed to operate using an aerobic process. The conditions required for aerobic operation are (1) sufficient free, elemental oxygen; (2) sufficient organic matter (food); (3) sufficient water; (4) enough nitrogen and phosphorus (nutrients) to permit oxidation of the available carbon materials; (5) proper pH (6.5 to 9.0); and (6) lack of toxic materials.

This chapter provides microbiology fundamentals specifically targeted to the needs of water and wastewater specialists.

11.2 MICROBIOLOGY: WHAT IS IT?

Biology is generally defined as the study of living organisms (i.e., the study of life). *Microbiology* is a branch of biology that deals with the study of microorganisms so small in size that they must be studied under a microscope. Microorganisms of interest to the water/wastewater operator include bacteria, protozoa, viruses, algae, and a few others.

Note: The science and study of bacteria is known as bacteriology (discussed later).

As mentioned, waterworks operators' primary concern is how to control microorganisms that cause waterborne diseases — waterborne pathogens — to protect the consumer (human and animal). Wastewater operators have the same microbiological concerns as water operators, but instead of directly purifying water for consumer consumption, their focus is on removing harmful pathogens from the wastestream before outfalling it to the environment. To summarize, each technical occupation, water and wastewater operator, in regards to its reliance on knowledge of microbiological principles, is described in the following:

1. Water operators are concerned with water supply and water purification through a treatment process. In treating water, the primary concern is producing potable water that is safe to drink (free of pathogens) with no accompanying offensive characteristics such as foul taste and odor. The treatment operator must possess a wide range of knowledge in order to correctly examine water for pathogenic microorganisms and to determine the type of treatment necessary

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to ensure the water quality of the end product, potable water, meets regulatory requirements.

2. As mentioned, wastewater operators are also concerned with water quality. However, they are not as concerned as water specialists with total removal or reduction of most nonpathogenic microorganisms. The wastewater treatment process actually benefits from microorganisms that act to degrade organic compounds, stabilizing organic matter in the wastestream. Wastewater operators must be trained to operate the treatment process in a manner that controls the growth of microorganisms and puts them to work — to the benefit of the process. Moreover, to fully understand wastewater treatment, it is necessary to determine which microorganisms are present and how they function to break down components in the wastewater stream. The operator must then ensure that before outfalling or dumping treated effluent into the receiving body the microorganisms that worked so hard to degrade organic waste products, especially the pathogenic microorganisms, are not discharged from the plant with effluent as viable organisms.[2]

11.3 WATER AND WASTEWATER MICROORGANISMS

As mentioned, microorganisms of interest to water and wastewater operators include bacteria, protozoa, rotifers, viruses, algae, fungi, and nematodes. These organisms are the most diverse group on earth and occupy important niches in the ecosystem. Their simplicity and minimal survival requirements allow them to exist in diverse situations.

Because they are a major health concern, water treatment specialists are mostly concerned about how to control microorganisms that cause waterborne diseases. These waterborne diseases are carried by waterborne pathogens (i.e., bacteria, virus, protozoa, etc.).

Wastewater operators are mostly concerned about the millions of organisms that arrive at the plant as part of the influent. The majority of these organisms are nonpathogenic and beneficial to plant operations. These operations benefit from biological treatment processes that provide the similar biological reactions that would occur in the receiving waters if they had adequate capacity to assimilate the wastes.

From a microbiological standpoint, the predominant species of microorganisms present in biological treatment depend on the characteristics of the influent, environmental conditions, process design, and the mode of plant operation. There are, however, pathogenic organisms that may be present. These include the organisms responsible for diseases such as typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others.

To understand how to minimize or maximize growth of microorganisms and control pathogens one must study the structure and characteristics of the microorganisms. In the sections that follow, we will look at each of the major groups of microorganisms (those important to water and wastewater operators) in relation to their size, shape, types, nutritional needs, and control.

Note: In the water environment, Koren points out that water is not a medium for the growth of microorganisms. Instead, water is a means of transmission (a conduit for; hence, the name waterborne) of the pathogen to the place where an individual is able to consume it and there start the outbreak of disease. This view is contrary to the view taken by the average person. When the topic of waterborne disease is brought up, we might mistakenly assume that waterborne diseases are at home in water. Nothing could be further from the truth. A water-filled ambience is not the environment in which the pathogenic organism would choose to live, that is, if it has such a choice.[3] The point is that microorganisms do not normally grow, reproduce, languish, and thrive in watery surroundings. Pathogenic microorganisms temporarily residing in water are simply biding their time, going with the flow, waiting for their opportunity to meet up with their unsuspecting host or hosts. To a degree, when the pathogenic microorganism finds its host or hosts, it is finally home or may have found its final resting place.[4]

11.3.1 Key Terms

Key terms related to the discussion to follow and their basic definitions are listed below:

Algae simple plants, many microscopic, containing chlorophyll. Freshwater algae are diverse in shape, color, size, and habitat. They are the basic link in the conversion of inorganic constituents in water into organic constituents.

Algal bloom sudden spurts of algal growth that can affect water quality adversely and indicate potentially hazardous changes in local water chemistry.

Anaerobic able to live and grow in the absence of free oxygen.

Autotrophic organisms organisms that produce food from inorganic substances.

Bacteria single-cell, microscopic living organisms (single-celled microorganisms) that possess rigid cell walls. They may be aerobic, anaerobic,

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or facultative; they can cause disease; and some are important in pollution control.

Biogeochemical cycle the chemical interactions among the atmosphere, hydrosphere, and biosphere.

Coliform organism microorganisms found in the intestinal tract of humans and animals. Their presence in water indicates fecal pollution and potentially adverse contamination by pathogens.

Denitrification the anaerobic biological reduction of nitrate to nitrogen gas.

Fungi simple plants lacking that ability to produce energy through photosynthesis.

Heterotrophic organisms organisms that are dependent on organic matter for foods.

Prokaryotic cell the simple cell type, characterized by the lack of a nuclear membrane and the absence of mitochondria.

Virus the smallest form of microorganisms capable of causing disease.

11.3.2 Microorganisms (in General)

The microorganisms we are concerned with are tiny organisms that make up a large and diverse group of free-living forms; they exist either as single cell, cell bunches, or clusters.

Found in abundance almost anywhere on earth, the vast majority of microorganisms are not harmful. Many microorganisms, or microbes, occur as single cells (unicellular). Others are multicellular; and others, viruses, do not have a true cellular appearance.

For the most part, a single microbial cell exhibits the characteristic features common to other biological systems, such as metabolism, reproduction, and growth.

11.3.3 Classification

For centuries, scientists classified the forms of life visible to the naked eye as either animal or plant. The Swedish naturalist Carolus Linnaeus organized much of the current knowledge about the living things in 1735.

The importance of organizing or classifying organisms cannot be overstated. Without a classification scheme, it would be difficult to establish a criteria for identifying organisms and to arrange similar organisms into groups. Probably the most important reason for classifying organisms is to make things less confusing.[5]

Linnaeus was quite innovative in the classification of organisms. One of his innovations is still with us today: the binomial system of nomenclature. Under the binomial system, all organisms are generally described by a two-word scientific name, the genus and species. Genus and species are groups that are part of hierarchy of groups of increasing size, based on their taxonomy. This hierarchy follows:

Kingdom
Phylum
Class
Order
Family
Genus
Species

Using this system, a fruit fly might be classified as:

Animalia
Arthropoda
Insecta
Diptera
Drosophilidae
Drosophila
melanogaster

This means that this organism is the species *melanogaster* in the genus *Drosophila* in the family Drosophilidae in the order Diptera in the class Insecta in the phylum Arthropoda in the kingdom Animalia.

To further illustrate how the hierarchical system is exemplified by the classification system, we provide the standard classification of the mayfly (a burrowing macroinvertebrate; discussed in greater detail in Chapter 12):

Mayfly	
Kingdom	Animalia
Phylum	Arthropoda
Class	Insecta
Order	Ephermeroptera
Family	Ephemeridae
Genus	*Hexagenia*
Species	*limbata*

Utilizing this hierarchy and Linnaeus's binomial system of nomenclature, the scientific name of any organism (as stated previously) includes both the generic and specific names. In the above instances, to uniquely name the species it is necessary to supply the genus and the species, *Drosophila melanogaster* (i.e., the fruit fly) and *Hexagenia limbota* (mayfly). As shown, the first letter of the generic name is usually capitalized, hence, for example, *E. coli* indicates that *coli* is the species and *Escherichia* (abbreviated to E.) is the genus. The largest, most inclusive category — the kingdom — is plant. The names are always in Latin, so they are usually printed in italics or underlined. Some organisms also have English common names. Microbe names of particular interest in water and wastewater treatment include:

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TABLE 11.1
Simplified Classification of Microorganisms

Kingdom	Members	Cell Classification
Animal	Rotifers	
	Crustaceans	
	Worms and larvae	Eucaryotic
Plant	Ferns	
	Mosses	
Protista	Protozoa	
	Algae	
	Fungi	
	Bacteria	Prokaryotic
	Lower algae forms	

Source: From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revsed ed.), Technomic Publ., Lancaster, PA, 2000.

1. *Escherichia coli* — a coliform bacterium
2. *Salmonella typhi* — the typhoid bacillus
3. *Giardia lamblia* — a protozoan
4. *Shigella* spp.
5. *Vibrio cholerae*
6. *Campylobacter*
7. *Leptospira* spp.
8. *Entamoeba histolytica*
9. *Crytosporidia*

Note: *Escherichia coli* is commonly known as simply *E. coli*, while *Giardia lamblia* is usually referred to by only its genus name, *Giardia.*

Generally, we use a simplified system of microorganism classification in water science, breaking down classification into the kingdoms of animal, plant, and protista. As a rule, the animal and plant kingdoms contain all the multicell organisms, and the protists contain all single-cell organisms. Along with microorganism classification based on the animal, plant, and protista kingdoms, microorganisms can be further classified as being eucaryotic or prokaryotic (see Table 11.1).

Note: A eucaryotic organism is characterized by a cellular organization that includes a well-defined nuclear membrane. The prokaryotes have structural organization that sets them off from all other organisms. They are simple cells characterized by a nucleus lacking a limiting membrane, an endoplasmic reticulum, chloroplasts, and mitochondria. They are remarkably adaptable, existing abundantly in the soil, the sea, and freshwater.

11.3.4 Differentiation

Differentiation among the higher forms of life is based almost entirely upon morphological (form or structure) differences. However, differentiation (even among the higher forms) is not as easily accomplished as you might expect because normal variations among individuals of the same species occur frequently.

Because of this variation even within a species, securing accurate classification when dealing with single-celled microscopic forms that present virtually no visible structural differences becomes extremely difficult. Under these circumstances, considering physiological, cultural, and chemical differences are necessary, as well as structure and form. Differentiation among the smaller groups of bacteria is based almost wholly upon chemical differences.

11.3.5 The Cell

The structural and fundamental unit of both plants and animals, no matter how complex, is the cell. Since the 19th century, scientists have known that all living things, whether animal or plant, are made up of cells. A typical cell is an entity, isolated from other cells by a membrane or cell wall. The cell membrane contains protoplasm and the nucleus (see Figure 11.1). The protoplasm within the cell is a living mass of viscous, transparent material. Within the protoplasm is a dense spherical mass called the nucleus or nuclear material.

In a typical mature plant cell, the cell wall is rigid and is composed of nonliving material, while in the typical animal cell, the wall is an elastic living membrane. Cells

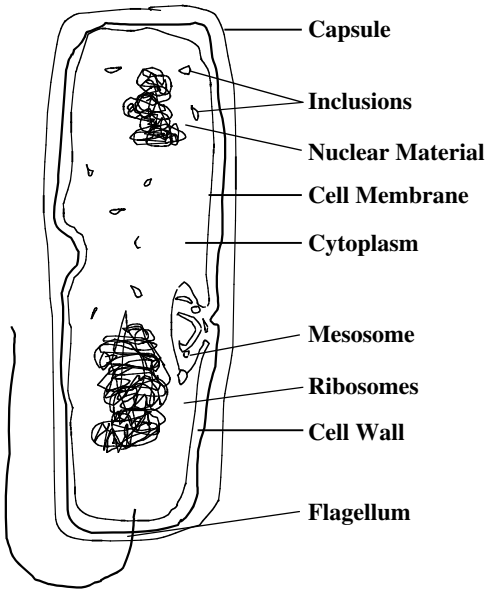

FIGURE 11.1 Bacterial cell. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

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exist in a very great variety of sizes, shapes, and functions. Their average size ranges from bacteria too small to be seen with the light microscope to the largest known single cell, the ostrich egg. Microbial cells also have an extensive size range, some being larger than human cells.[6]

Note: The nucleus cannot always be observed in bacteria.

11.3.5.1 Structure of the Bacterial Cell

The structural form and various components of the bacterial cell are probably best understood by referring to the simplified diagram of a rod-form bacterium shown in Figure 11.1. (Note: When studying Figure 11.1, keep in mind that cells of different species may differ greatly, both in structure and chemical composition; for this reason no typical bacterium exists. Not all bacteria have all of the features shown in Figure 11.1 and some bacteria have structures not shown in the figure.)

11.3.5.1.1 Capsules

Bacterial capsules (see Figure 11.1) are organized accumulations of gelatinous materials on cell walls, in contrast to slime layers (a water secretion that adheres loosely to the cell wall and commonly diffuses into the cell), which are unorganized accumulations of similar material. The capsule is usually thick enough to be seen under the ordinary light microscope (macrocapsule), while thinner capsules (microcapsules) can be detected only by electron microscopy.[7]

The production of capsules is determined largely by genetics as well as environmental conditions, and depends on the presence or absence of capsule-degrading enzymes and other growth factors. Varying in composition, capsules are mainly composed of water; the organic contents are made up of complex polysaccharides, nitrogen-containing substance, and polypeptides.

Capsules confer several advantages when bacteria grow in their normal habitat. These include helping to:

1. Prevent desiccation
2. Resist phagocytosis by host phagocytic cells
3. Prevent infection by bateriophages
4. Aid bacterial attachment to tissue surfaces in plant and animal hosts or to surfaces of solids objects in aquatic environments

Capsule formation often correlates with pathogenicity.

11.3.5.1.2 Flagella

Many bacteria are motile, and this ability to move independently is usually attributed to a special structure, the flagella (singular: flagellum). Depending on species, a cell may have a single flagellum (see Figure 11.1) (monotrichous bacteria; trichous means hair); one flagellum at each end (amphitrichous bacteria; amphi means on both sides); a tuft of flagella at one or both ends (lophotrichous bacteria; lopho means tuft); or flagella that arise all over the cell surface (peritrichous bacteria; peri means around).

A flagellum is a threadlike appendage extending outward from the plasma membrane and cell wall. Flagella are slender, rigid, locomotor structures, and measure about 20 μm across and up to 15 to 20 μm long.

Flagellation patterns are very useful in identifying bacteria and can be seen by light microscopy, but only after being stained with special techniques designed to increase their thickness. The detailed structure of flagella can be seen only in the electron microscope.

Bacterial cells benefit from flagella in several ways. They can increase the concentration of nutrients or decrease the concentration of toxic materials near the bacterial surfaces by causing a change in the flow rate of fluids. They can also disperse flagellated organisms to areas where colony formation can take place. The main benefit of flagella to organisms is their increased ability to flee from areas that might be harmful.

11.3.5.1.3 Cell Wall

The main structural component of most prokaryotes is the rigid *cell wall* (see Figure 11.1). Functions of the cell wall include:

1. Providing protection for the delicate protoplast from osmotic lysis (bursting)
2. Determining a cell's shape
3. Acting as a permeability layer that excludes large molecules and various antibiotics and playing an active role in regulating the cell's intake of ions
4. Providing a solid support for flagella

Cell walls of different species may differ greatly in structure, thickness, and composition. The cell wall accounts for about 20 to 40% of a bacterium's dry weight.

11.3.5.1.4 Plasma Membrane (Cytoplasmic Membrane)

Surrounded externally by the cell wall and composed of a lipoprotein complex, the *plasma membrane* or cell membrane is the critical barrier, separating the inside from outside the cell (see Figure 11.1). About 7 to 8 μm thick and comprising 10 to 20% of a bacterium's dry weight, the plasma membrane controls the passage of all material into and out of the cell. The inner and outer faces of the plasma membrane are embedded with water-loving (hydrophilic) lips, whereas the interior is hydrophobic. Control of material into the cell is accomplished by screening, as well as by electric charge. The plasma membrane is the site of the surface charge of the bacteria.

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In addition to serving as an osmotic barrier that passively regulates the passage of material into and out of the cell, the plasma membrane participates in the entire active transport of various substances into the bacterial cell. Inside the membrane, many highly reactive chemical groups guide the incoming material to the proper points for further reaction. This active transport system provides bacteria with certain advantages, including the ability to maintain a fairly constant intercellular ionic state in the presence of varying external ionic concentrations. In addition to participating in the uptake of nutrients, the cell membrane transport system participates in waste excretion and protein secretions.

11.3.5.1.5 Cytoplasm

Within a cell and bounded by the cell membrane is a complicated mixture of substances and structures called the cytoplasm (see Figure 11.1). The cytoplasm is a water-based fluid containing ribosomes; ions; enzymes; nutrients; storage granules (under certain circumstances); waste products; and various molecules involved in synthesis, energy metabolism, and cell maintenance.

11.3.5.1.6 Mesosome

A common intracellular structure found in the bacterial cytoplasm is the Mesosome (see Figure 11.1). Mesosomes are invaginations of the plasma membrane in the shape of tubules, vesicles, or lamellae. Their exact function is unknown. Currently many bacteriologists believe that mesosomes are artifacts generated during the fixation of bacteria for electron microscopy.

11.3.5.1.7 Nucleoid (Nuclear Body or Region)

The nuclear region of the prokaryotic cell is primitive and a striking contrast to that of the eucaryotic cell (see Figure 11.1). Prokaryotic cells lack a distinct nucleus, the function of the nucleus being carried out by a single, long, double strand of DNA that is efficiently packaged to fit within the nucleoid. The nucleoid is attached to the plasma membrane. A cell can have more than one nucleoid when cell division occurs after the genetic material has been duplicated.

11.3.5.1.8 Ribosomes

The bacterial cytoplasm is often packed with ribosomes (see Figure 11.1). *Ribosomes* are minute, rounded bodies made of RNA and are loosely attached to the plasma membrane. Ribosomes are estimated to account for about 40% of a bacterium's dry weight; a single cell may have as many as 10,000 ribosomes. Ribosomes are the site of protein synthesis and are part of the translation process.

11.3.5.1.9 Inclusions

Inclusions (or storage granules) are often seen within bacterial cells (see Figure 11.1). Some inclusion bodies are not bound by a membrane and lie free in the cytoplasm. A single-layered membrane about 2 to 4 μm thick encloses other inclusion bodies. Many bacteria produce polymers that are stored as granules in the cytoplasm.

11.4 BACTERIA

The simplest wholly contained life systems are bacteria or prokaryotes, the most diverse group of microorganisms. As mentioned, they are among the most common microorganisms in water. Bacteria are primitive, unicellular (single celled) organisms, possessing no well-defined nucleus and presenting a variety of shapes and nutritional needs. Bacteria contain about 85% water and 15% ash or mineral matter. The ash is largely composed of sulfur, potassium, sodium, calcium, and chlorides, with small amounts of iron, silicon and magnesium. Bacteria reproduce by binary fission.

Note: Binary fission occurs when one organism splits or divides into two or more new organisms.

Bacteria, once called the smallest living organisms (now it is known that smaller forms of matter exhibit many of the characteristics of life), range in size from 0.5 to 2 μm in diameter and about 1 to 10 μm long.

Note: A micron is a metric unit of measurement equal to one thousandth of a millimeter. To visualize the size of bacteria, consider that about 1000 bacteria lying side-by-side would reach across the head of a straight pin.

Bacteria are categorized into three general groups based on their physical form or shape (though almost every variation has been found; see Table 11.2). The simplest form is the sphere. Spherical shaped bacteria are called cocci. Cocci mean berries. They are not necessarily perfectly round, but may be somewhat elongated, flattened on one side, or oval. Rod shaped bacteria are called bacilli. Spiral shaped bacteria (called spirilla), which have one or more twists and are never straight, make up the third group (see Figure 11.2). Such formations are usually characteristic of a particular genus or species. Within these three

TABLE 11.2
Forms of Bacteria

	Technical Name		
Form	**Singular**	**Plural**	**Example**
Sphere	Coccus	Cocci	Streptococcus
Rod	Bacillus	Bacilli	Bacillus typhosis
Curved or spiral	Spirillum	Spirilla	Spirillum cholera

Source: From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revsed ed.), Technomic Publ., Lancaster, PA, 2000.

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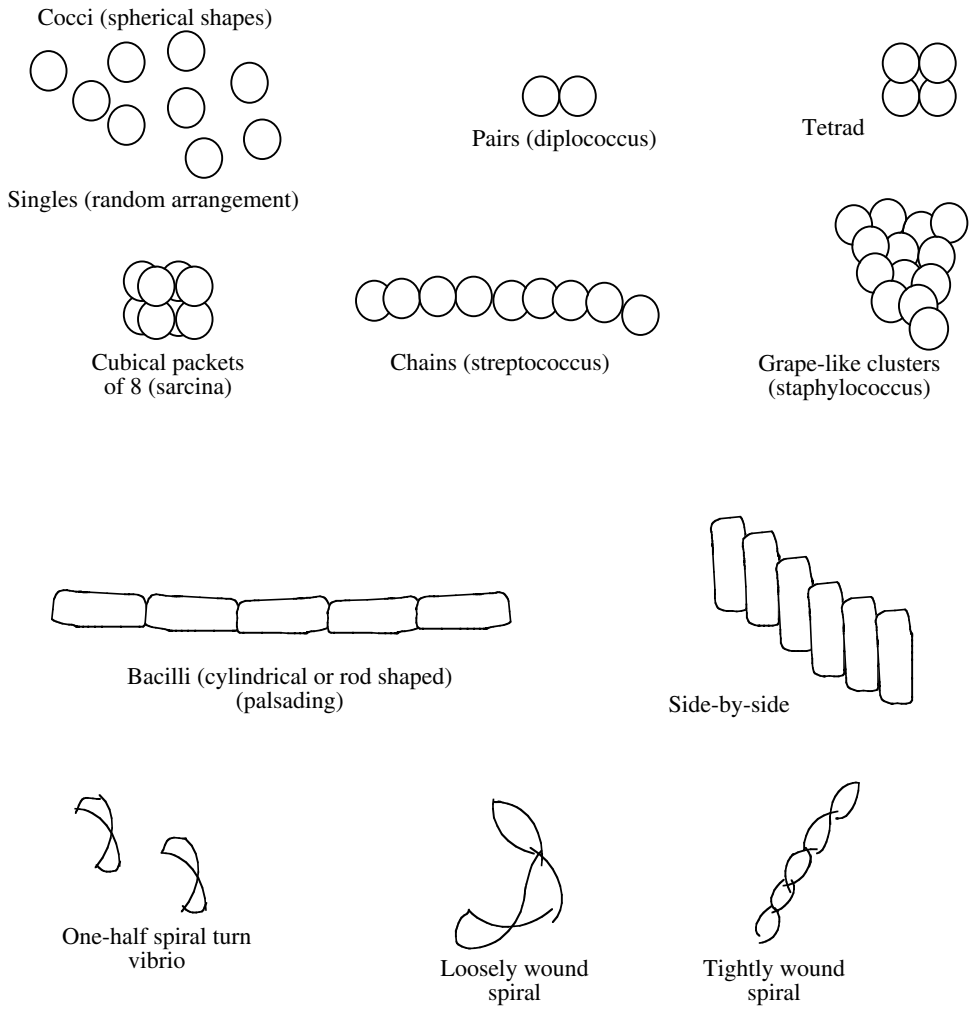

FIGURE 11.2 Bacterial shapes and arrangements. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

groups are many different arrangements. Some exist as single cells, while others exist as pairs, packets of four or eight, chains, or clumps.

Most bacteria require organic food to survive and multiply. Plant and animal material that gets into the water provides the food source for bacteria. Bacteria convert the food to energy and use the energy to make new cells. Some bacteria can use inorganics (e.g., minerals such as iron) as an energy source and exist and multiply even when organics (pollution) are not available.

11.4.1 Bacterial Growth Factors

Several factors affect the rate at which bacteria grow, including temperature, pH, and oxygen levels. The warmer the environment, the faster the rate of growth. Generally, for each increase of 10°C, the growth rate doubles. Heat can also be used to kill bacteria.

Most bacteria grow best at neutral pH. Extreme acidic or basic conditions generally inhibit growth, though some bacteria may require acidic and some require alkaline conditions for growth.

Bacteria are aerobic, anaerobic, or facultative. If aerobic, they require free oxygen in the aquatic environment. Anaerobic bacteria exist and multiply in environments that lack dissolved oxygen (DO). Facultative bacteria (e.g., iron bacteria) can switch from an aerobic to anaerobic growth or grow in an anaerobic or aerobic environment.

Under optimum conditions, bacteria grow and reproduce very rapidly. As stated previously, bacteria reproduce by binary fission.

An important point to consider in connection with bacterial reproduction is the rate at which the process can occur. The total time required for an organism to reproduce and the offspring to reach maturity is called generation time. Bacteria growing under optimal conditions can double their number about every 20 to 30 min. Obviously, this generation time is very short compared to that of higher plants and animals. Bacteria continue to grow at this rapid rate as long as nutrients hold out — even the

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smallest contamination can result in a sizable growth in a very short time.

Note: Even though wastewater can contain bacteria counts in the millions per milliliter, in wastewater treatment and under controlled conditions, bacteria can help to destroy and to identify pollutants. In such a process, bacteria stabilize organic matter (e.g., activated sludge processes), assisting the treatment process in producing effluent that does not impose an excessive oxygen demand on the receiving body. Coliform bacteria can be used as an indicator of pollution by human or animal wastes.

11.4.2 Destruction of Bacteria

In water and wastewater treatment, the destruction of bacteria is usually called disinfection.

Note: Inhibiting the growth of microorganisms is termed antisepsis, while destroying them is called disinfection.

Disinfection does not mean that all microbial forms are killed. The total destruction of all microbial forms is called sterilization. However, disinfection does reduce the number of disease-causing organisms to an acceptable number. Growing, thriving bacteria are easy to control by disinfection. Some bacteria, however, form spores — survival structures — that are much more difficult to destroy. It is difficult for the disinfection to penetrate the protective shell of the spore material.

11.4.3 Waterborne Bacteria

All surface waters contain bacteria. Waterborne bacteria, as we have said, are responsible for infectious epidemic diseases.

Bacterial numbers increase significantly during storm events when streams are high. Heavy rainstorms increase stream contamination by washing material from the ground surface into the stream. After the initial washing occurs, few impurities are left to be washed into the stream, which may then carry relatively clean water. A river or stream of good water quality shows its highest bacterial numbers during rainy periods; a much-polluted stream may show the highest numbers during low flows because of the constant influx of pollutants and decreased dilution ability.

Water and wastewater operators are primarily concerned with bacterial pathogens responsible for disease. These pathogens enter potential drinking water supplies through fecal contamination and are ingested by humans if the water is not properly treated and disinfected.

Note: Regulations require that owners of all public water supplies collect water samples and deliver them to a certified laboratory for bacteriological examination at least monthly. The number of samples required is usually in accordance with federal standards, which generally require that one sample per month be collected for each 1000 persons served by the waterworks.

11.5 PROTOZOA

Protozoa (or first animals) are a large group of eucaryotic organisms of more than 50,000 known species belonging to the kingdom Protista that have adapted a form of cell to serve as the entire body. In fact, protozoa are one-celled animal-like organisms with complex cellular structures. In the microbial world, protozoa are giants, many times larger than bacteria. They range in size from 4 to 500 µm. The largest ones can almost be seen by the naked eye. They can exist as solitary or independent organisms (e.g., the stalked ciliates [see Figure 11.3] such as *Vorticella* sp.), or they can colonize like the sedentary *Carchesium* sp. Protozoa get their name because they employ the same type of feeding strategy as animals. That is, they are heterotrophic, meaning they obtain cellular energy from organic substances such as proteins. Most are harmless, but some are parasitic. Some forms have two life stages: active trophozoites (capable of feeding) and dormant cysts.

The major groups of protozoa are based on their method of locomotion (motility). For example, the *Mastigophora* are motile by means of one of more flagella (e.g., *Giardia lamblia*), and the *Ciliophora* are motile by means of shortened modified flagella called cilia (short hair-like structures that beat rapidly and propel them through the water). The *Sarcodina* are motile by means of amoeboid movement (streaming or gliding action — the shape of amoebae change as they stretch, then contract, from place to place), while the nonmotile *Sporozoa* are simply swept along, riding the current of the water.

Protozoa consume organics to survive; their favorite food is bacteria. Protozoa are mostly aerobic or facultative in regards to oxygen requirements. Toxic materials, pH, and temperature affect protozoan rates of growth in the same way as they affect bacteria.

Most protozoan life cycles alternate between an active growth phase (trophozoites) and a resting stage (cysts). Cysts are extremely resistant structures that protect the organism from destruction when it encounters harsh environmental conditions, including chlorination.

Note: Those protozoa not completely resistant to chlorination require higher disinfectant concentrations and longer contact time for disinfection than normally used in water treatment.

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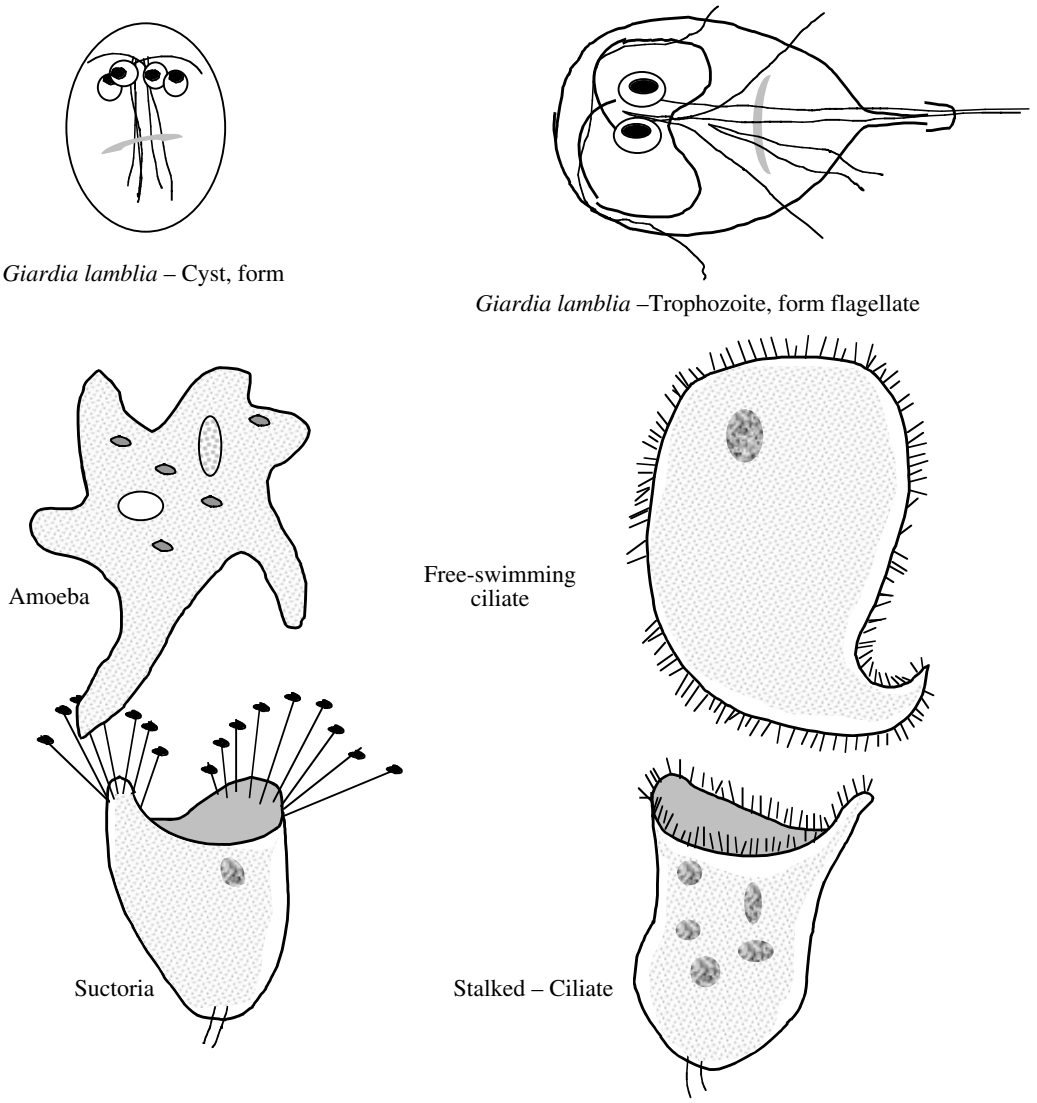

FIGURE 11.3 Protozoa. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

The three protozoa and the waterborne diseases associated with them of most concern to the waterworks operator are:

1. *Entamoeba histolytica* — amoebic dysentery
2. *Giardia lamblia* — giardiasis
3. *Cryptosporidium* — cryptosporidiosis

In wastewater treatment, protozoa are a critical part of the purification process and can be used to indicate the condition of treatment processes. Protozoa normally associated with wastewater include amoeba, flagellates, free-swimming ciliates, and stalked ciliates.

Amoebas are associated with poor wastewater treatment of a young biosolids mass (see Figure 11.3). They move through wastewater by a streaming or gliding motion. Moving the liquids stored within the cell wall effects this movement. They are normally associated with an effluent high in biochemical oxygen demands (BODs) and suspended solids.

Flagellates (flagellated protozoa) have a single, long hair-like or whip-like projection (flagella) that is used to propel the free-swimming organisms through wastewater and to attract food (see Figure 11.3). Flagellated protozoa are normally associated with poor treatment and a young biosolids age. When the predominate organism is the flagellated protozoa, the plant effluent will contain large amounts of BODs and suspended solids.

The free-swimming ciliated protozoan uses its tiny, hair-like projections (cilia) to move itself through the wastewater and to attract food (see Figure 11.3). The free-swimming ciliated protozoan is normally associated with a moderate biosolids age and effluent quality. When the free-swimming ciliated protozoan is the predominate

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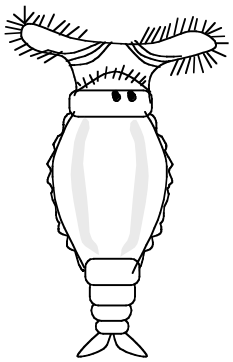

FIGURE 11.4 Philodina, a common rotifier. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

organism, the plant effluent will normally be turbid and contain a high amount of suspended solids.

The stalked ciliated protozoan attaches itself to the wastewater solids and uses its cilia to attract food (see Figure 11.3). The stalked ciliated protozoan is normally associated with a plant effluent that is very clear and contains low amounts of both BODs and suspended solids.

Rotifers make up a well-defined group of the smallest, simplest multicellular microorganisms and are found in nearly all aquatic habitats (see Figure 11.4). Rotifers are a higher life form associated with cleaner waters. Normally found in well-operated wastewater treatment plants, they can be used to indicate the performance of certain types of treatment processes.

11.6 MICROSCOPIC CRUSTACEANS

Because they are important members of freshwater zooplankton, microscope crustaceans are of interest to water and wastewater operators. These microscopic organisms are characterized by a rigid shell structure. They are multicellular animals that are strict aerobes, and as primary producers, they feed on bacteria and algae. They are important as a source of food for fish. Additionally, microscopic crustaceans have been used to clarify algae-laden effluents form oxidations ponds. *Cyclops* and *Daphnia* are two microscopic crustaceans of interest to water and wastewater operators.

11.7 VIRUSES

Viruses are very different from the other microorganisms. Consider their size relationship, for example. Relative to size, if protozoa are the Goliaths of microorganisms, then viruses are the Davids. Stated more specifically and accurately, viruses are intercellular parasitic particles that are the smallest living infectious materials known — the midgets of the microbial world. Viruses are very simple life forms consisting of a central molecule of genetic material surrounded by a protein shell called a capsid — and sometimes by a second layer called an envelope. They contain no mechanisms by which to obtain energy or reproduce on their own; they must have a host to live. After they invade the cells of their specific host (animal, plant, insect, fish, or even bacteria), they take over the host's cellular machinery and force it to make more viruses. In the process, the host cell is destroyed and hundreds of new viruses are released into the environment.

The viruses of most concern to the waterworks operator are the pathogens that cause hepatitis, viral gastroenteritis, and poliomyelitis.

Smaller and different from bacteria, viruses are prevalent in water contaminated with sewage. Detecting viruses in water supplies is a major problem because of the complexity of nonroutine procedures involved, though experience has shown that the normal coliform index can be used as a rough guide for viruses as for bacteria. More attention must be paid to viruses whenever surface water supplies have been used for sewage disposal.

Viruses occur in many shapes, including long slender rods, elaborate irregular shapes and geometric polyhedrals (see Figure 11.5).

Viruses are difficult to destroy by normal disinfection practices. They require increased disinfectant concentration and contact time for effective destruction.

Note: Viruses that infect bacterial cells cannot infect and replicate within cells of other organisms. It is possible to utilize the specificity to identify bacteria, a procedure called phage typing.

11.8 ALGAE

You do not have to be a water or wastewater operator to understand that algae can be a nuisance. Many ponds and lakes in the U.S. are currently undergoing eutrophication, the enrichment of an environment with inorganic substances (e.g., phosphorus and nitrogen), causing excessive algae growth and premature aging of the water body. The average person may not know what eutrophication means, but when it occurs and especially when filamentous algae like *Caldophora* break loose in a pond or lake and washes ashore, algae makes its stinking, noxious presence known.

Algae are a form of aquatic plants and are classified by color (e.g., green algae, blue-green algae, golden-brown algae, etc.). Algae come in many shapes and sizes (see Figure 11.6). Although they are not pathogenic, algae do cause problems with water and wastewater treatment plant operations. They grow easily on the walls of troughs and basins, and heavy growth can plug intakes and screens. Additionally, some algae release chemicals that give off undesirable tastes and odors.

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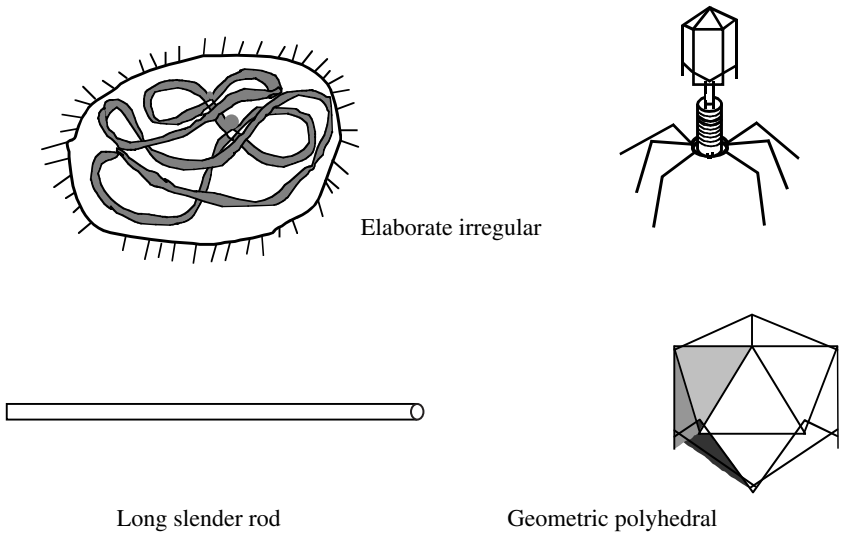

FIGURE 11.5 Virus shapes. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

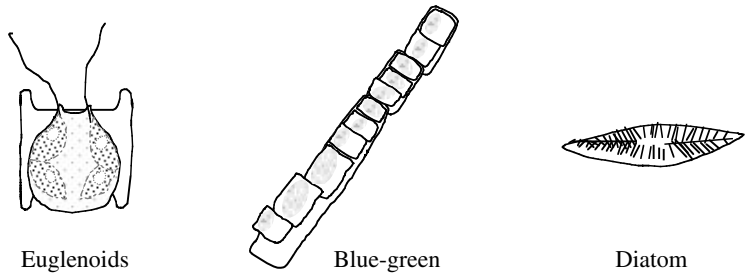

FIGURE 11.6 Algae. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

Algae are also commonly classified based on their cellular properties or characteristics. Several characteristics are used to classify algae including:

1. Cellular organization and cell wall structure
2. Nature of the chlorophyll(s)
3. Type of motility, if any
4. Carbon polymers that are produced and stored
5. Reproductive structures and methods

Many algae (in mass) are easily seen by the naked eye, while others are microscopic. They occur in fresh and polluted water, as well as in salt water. Since they are plants, they are capable of using energy from the sun in photosynthesis. They usually grow near the surface of the water because light cannot penetrate very far through the water.

Algae are controlled in raw waters with chlorine and potassium permanganate. Algae blooms in raw water reservoirs are often controlled with copper sulfate.

Note: By producing oxygen, which is utilized by other organisms including animals, algae play an important role in the balance of nature.

11.9 FUNGI

Fungi are of relatively minor importance in water/wastewater operations (except for biosolids composting, where they are critical). Fungi, like bacteria, are also extremely diverse. They are multicellular, autotrophic, photosynthetic protists. They grow as filamentous, mold-like forms or as yeast-like (single-celled) organisms. They feed on organic material.

Note: Aquatic fungi grow as parasites on living plants or animals and as saprophytes on those that are dead.

11.10 NEMATODES AND FLATWORMS (WORMS)

Along with inhabiting organic mud, worms also inhabit biological slimes; they have been found in activated sludge and in trickling filter slimes (wastewater treatment processes). Microscopic in size, they range in length from 0.5 to 3 mm and in diameter from 0.01 to 0.05 mm. Most species have a similar appearance. They have a body that

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is covered by cuticle and are cylindrical, nonsegmented, and taper at both ends.

These organisms continuously enter wastewater treatment systems, primarily through attachment to soils that reach the plant through inflow and infiltration (I & I). They are present in large, often highly variable numbers, but as strict aerobes, they are found only in aerobic treatment processes where they metabolize solid organic matter.

Once nematodes are firmly established in the treatment process, they can promote microfloral activity and decomposition. They crop bacteria in both the activated sludge and trickling filter systems. Their activities in these systems enhance oxygen penetration by tunneling through floc particles and biofilm. In activated sludge processes, they are present in relatively small numbers because the liquefied environment is not a suitable habitat for crawling, which they prefer over the free-swimming mode. In trickling filters where the fine stationary substratum is suitable to permit crawling and mating, nematodes are quite abundant.

Along with preferring the trickling filter habitat, nematodes play a beneficial role in this habitat. For example, they break loose portions of the biological slime coating the filter bed. This action prevents excessive slime growth and filter clogging. They also aid in keeping slime porous and accessible to oxygen by tunneling through slime.

In the activated sludge process, the nematodes play important roles as agents of better oxygen diffusion. They accomplish this by tunneling through floc particles. They also act as parameters of operational conditions in the process, such as low DO levels (anoxic conditions) and the presence of toxic wastes.

Environmental conditions have an impact on the growth of nematodes. For example, in anoxic conditions their swimming and growth is impaired. The most important condition they indicate is when the wastewater strength and composition has changed. Temperature fluctuations directly affect their growth and survival; population decreases when temperatures increase.

Aquatic flatworms (improperly named because they are not all flat) feed primarily on algae. Because of their aversion to light, they are found in the lower depths of pools. Two varieties of flatworms are seen in wastewater treatment processes: microtubellarians are more than flat and average about 0.5 to 5 mm in size, and macrotubellarians (planarians) are more flat than round and average about 5 to 20 mm in body size. Flatworms are very hardy and can survive in wide variations in humidity and temperature. As inhabitants of sewage sludge, they play an important part in sludge stabilization and as bioindicators or parameters of process problems. For example, their inactivity or sluggishness might indicate a low DO level or the presence of toxic wastes.

Surface waters grossly polluted with organic matter (especially domestic sewage) have a fauna that is capable of thriving in very low concentrations of oxygen. A few species of tubificid worms dominate this environment. Pennak reports that the bottoms of severely polluted streams can be literally covered with a "writhing" mass of this tubificids.[8]

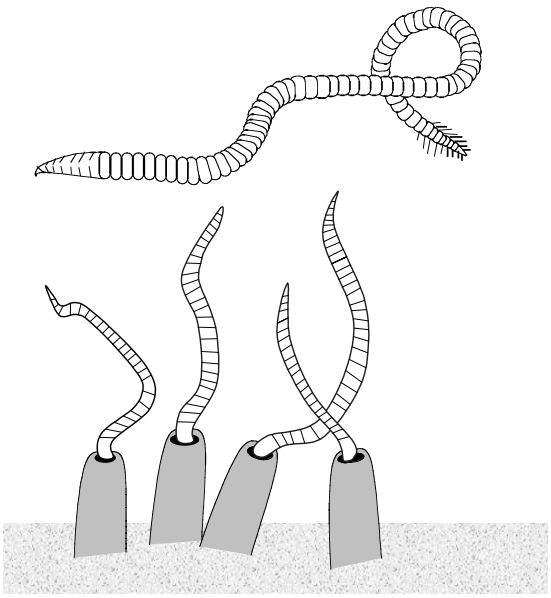

FIGURE 11.7 Tubificid worm(s). (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

The *Tubifex* (commonly known as sludge worms) are small, slender, reddish worms that normally range in length from 25 to about 50 mm. They are burrowers; their posterior end protrudes to obtain nutrients (see Figure 11.7). When found in streams, *Tubifex* are indicators of pollution.

11.11 PATHOGENIC PROTOZOA AND HELMINTHS (WATER)

The primary goal in water treatment is to protect the consumer of potable drinking water from disease. Drinking water safety is a worldwide concern. Drinking nontreated or improperly treated water is a major cause of illness in developing countries.

Water contains several biological (as well as chemical) contaminants that must be removed efficiently in order to produce safe drinking water that is also aesthetically pleasing to the consumer. The finished water must be free of microbial pathogens and parasites, turbidity, color, and taste and odor. To achieve this goal, raw surface water or groundwater is subjected to a series of treatment processes that will be described in detail later. Disinfection alone is sufficient if the raw water originates from a protected source. More commonly, several processes are used to treat water. For example, disinfection may be combined with coagulation, flocculation, and filtration.

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As mentioned, several unit processes are used in the water treatment process to produce microbiologically (and chemically) safe drinking water. The extent of treatment depends on the source of raw water; surface waters generally require more treatment than groundwaters. With the exception of disinfection, the other unit processes in the treatment train do not specifically address the destruction or removal of pathogens.

Water treatment unit processes include:

1. Storage of raw water
2. Prechlorination
3. Coagulation-flocculation
4. Water softening
5. Filtration
6. Disinfection

Although filtration and disinfection are the primary means of removing contaminants and pathogens from drinking water supplies, in each of these unit processes, reduction or destruction of pathogens is accomplished but is variable and is influenced by a number of factors such as sunlight, sedimentation, and temperature.

The water treatment unit processes mentioned above are important and are described in detail later in this text. For the moment, because of relatively recent events involving pathogenic protozoa causing adverse reactions, including death, to consumers in various locations in the U.S. (and elsewhere), it is important to turn our attention to these pathogenic protozoa. One thing is certain — these pathogenic protozoa have the full attention of water treatment operators everywhere.

11.11.1 Pathogenic Protozoa

As mentioned, certain types of protozoa can cause disease. Of particular interest to the drinking water practitioner are the *Entamoeba histolytica* (amebic dysentery and amebic hepatitis), *Giardia lamblia* (giardiasis), *Cryptosporidium* (cryptosporidiosis), and the emerging *Cyclospora* (cyclosporosis). Sewage contamination transports eggs, cysts, and oocysts of parasitic protozoa and helminthes (tapeworms, hookworms, etc.) into raw water supplies, leaving water treatment (in particular filtration) and disinfection as the means by which to diminish the danger of contaminated water for the consumer.

To prevent the occurrence of *Giardia* and *Cryptosporidium* spp. in surface water supplies, and to address increasing problems with waterborne diseases, the U.S. Environmental Protection Agency (EPA) implemented its Surface Water Treatment Rule (SWTR) in 1989. The rule requires both filtration and disinfection of all surface water supplies as a means of primarily controlling *Giardia* spp. and enteric viruses. Since implementation of its SWTR, the EPA has also recognized that *Cryptosporidium* spp. is an agent of waterborne disease. In 1996, in its next series of surface water regulations, the EPA included *Cryptosporidium.*

To test the need for and the effectiveness of the EPA's SWTR, LeChevallier et al. conducted a study on the occurrence and distribution of *Giardia* and *Cryptosporidium* organisms in raw water supplies to 66 surface water filter plants. These plants were located in 14 states and 1 Canadian province. A combined immunofluorescence test indicated that cysts and oocysts were widely dispersed in the aquatic environment. *Giardia* spp. was detected in more than 80% of the samples. *Cryptosporidium* spp. was found in 85% of the sample locations. Taking into account several variables, *Giardia* or *Cryptosporidium* spp. were detected in 97% of the raw water samples. After evaluating their data, the researchers concluded that the SWTR might have to be upgraded (subsequently, it has been) to require additional treatment.[9]

11.11.1.1 *Giardia*

Giardia (gee-ar-dee-ah) *lamblia* (also known as hikers'/travelers' scourge or disease) is a microscopic parasite that can infect warm-blooded animals and humans. Although *Giardia* was discovered in the 19th century, not until 1981 did the World Health Organization (WHO) classify *Giardia* as a pathogen. An outer shell called a cyst that allows it to survive outside the body for long periods protects *Giardia*. If viable cysts are ingested, *Giardia* can cause the illness known as giardiasis, an intestinal illness that can cause nausea, anorexia, fever, and severe diarrhea. The symptoms last only for several days, and the body can naturally rid itself of the parasite in 1 to 2 months. However, for individuals with weakened immune systems, the body often cannot rid itself of the parasite without medical treatment.

In the U.S., *Giardia* is the most commonly identified pathogen in waterborne disease outbreaks. Contamination of a water supply by *Giardia* can occur in two ways: (1) by the activity of animals in the watershed area of the water supply, or (2) by the introduction of sewage into the water supply. Wild and domestic animals are major contributors in contaminating water supplies. Studies have also shown that, unlike many other pathogens, *Giardia* is not host-specific. In short, *Giardia* cysts excreted by animals can infect and cause illness in humans. Additionally, in several major outbreaks of waterborne diseases, the *Giardia* cyst source was sewage contaminated water supplies.

Treating the water supply can effectively control waterborne *Giardia*. Chlorine and ozone are examples of two disinfectants known to effectively kill *Giardia* cysts. Filtration of the water can also effectively trap and remove the parasite from the water supply. The combination of disinfection and filtration is the most effective water treatment process available today for preventing *Giardia* contamination.

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In drinking water, *Giardia* is regulated under the Surface Water Treatment Rule (SWTR). Although the SWTR does not establish a Maximum Contaminant Level for *Giardia*, it does specify treatment requirements to achieve at least 99.9% (3-log) removal and inactivation of *Giardia.* This regulation requires that all drinking water systems using surface water or groundwater under the influence of surface water to disinfect and filter the water. The Enhanced Surface Water Treatment Rule (ESWTR), which includes *Cryptosporidium* and further regulates *Giardia*, was established in December 1996.

11.11.1.1.1 Giardiasis[10]

During the past 15 years, Giardiasis has been recognized as one of the most frequently occurring waterborne diseases in the U.S. *Giardia lamblia* cysts have been discovered in the U.S. in places as far apart as Estes Park, CO (near the Continental Divide); Missoula, MT; Wilkes-Barre, Scranton, and Hazleton, PA; and Pittsfield and Lawrence, MA, just to name a few.

Giardiasis is characterized by intestinal symptoms that usually last one week or more and may be accompanied by one or more of the following: diarrhea, abdominal cramps, bloating, flatulence, fatigue, and weight loss. Although vomiting and fever are commonly listed as relatively frequent symptoms, people involved in waterborne outbreaks in the U.S have not commonly reported them.

While most *Giardia* infections persist only for one or two months, some people undergo a more chronic phase that can follow the acute phase or may become manifest without an antecedent acute illness. Loose stools and increased abdominal gassiness with cramping, flatulence, and burping characterize the chronic phase. Fever is not common, but malaise, fatigue, and depression may ensue.[11] For a small number of people, the persistence of infection is associated with the development of marked malabsorption and weight loss.[12] Similarly, lactose (milk) intolerance can be a problem for some people. This can develop coincidentally with the infection or be aggravated by it, causing an increase in intestinal symptoms after ingestion of milk products.

Some people may have several of these symptoms without evidence of diarrhea or have only sporadic episodes of diarrhea every 3 or 4 days. Still others may not have any symptoms at all. Therefore, the problem may not be whether you are infected with the parasite or not, but how harmoniously you both can live together or how to get rid of the parasite (either spontaneously or by treatment) when the harmony does not exist or is lost.

Note: Three prescription drugs are available in the U.S. to treat giardiasis: quinacrine, metronidazole, and furazolidone. In a recent review of drug trials in which the efficacies of these drugs were compared, quinacrine produced a cure in 93% of patients, metronidazole cured 92%, and furazolidone cured about 84% of patients.[13]

Giardiasis occurs worldwide. In the U.S., *Giardia* is the parasite most commonly identified in stool specimens submitted to state laboratories for parasitologic examination. During a 3-year period, approximately 4% of one million stool specimens submitted to state laboratories tested positive for *Giardia*.[14] Other surveys have demonstrated *Giardia* prevalence rates ranging from 1 to 20%, depending on the location and ages of persons studied. Giardiasis ranks among the top 20 infectious diseases that cause the greatest morbidity in Africa, Asia, and Latin America; it has been estimated that about 2 million infections occur per year in these regions.[15] People who are at highest risk for acquiring *Giardia* infection in the U.S. may be placed into five major categories:

1. People in cities whose drinking water originates from streams or rivers, and whose water treatment process does not include filtration, or where filtration is ineffective because of malfunctioning equipment
2. Hikers, campers, and outdoor people
3. International travelers
4. Children who attend day-care centers, day-care center staff, and parents and siblings of children infected in day-care centers.
5. Homosexual men

People in categories 1, 2, and 3 have in common the same general source of infection (i.e., they acquire *Giardia* from fecally contaminated drinking water). The city resident usually becomes infected because the municipal water treatment process does not include the filter necessary to physically remove the parasite from the water. The number of people in the U.S. at risk (i.e., the number who receive municipal drinking water from unfiltered surface water) is estimated to be 20 million. International travelers may also acquire the parasite from improperly treated municipal waters in cities or villages in other parts of the world, particularly in developing countries. In Eurasia, only travelers to Leningrad appear to be at increased risk. In prospective studies, 88% of U.S. and 35% of Finnish travelers to Leningrad who had negative stool tests for *Giardia* on departure to the Soviet Union developed symptoms of giardiasis and had positive test for *Giardia* after they returned home.[16] With the exception of visitors to Leningrad, however, *Giardia* has not been implicated as a major cause of traveler's diarrhea — it has been detected in fewer than 2% of travelers who develop diarrhea. However, hikers and campers risk infection every time they drink untreated raw water from a stream or river.

Persons in categories 4 and 5 become exposed through more direct contact with feces or an infected person. This

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includes exposure to an infected child's soiled diapers (day-care center-associated cases) or direct or indirect anal-oral sexual practices in the case of homosexual men.

Although community waterborne outbreaks of giardiasis have received the greatest publicity in the U.S. during the past decade, about half of the *Giardia* cases discussed with the staff of the Centers for Disease Control (CDC) over a 3-year period had a day-care exposure as the most likely source of infection. Numerous outbreaks of *Giardia* in day-care centers have been reported in recent years. Infection rates for children in day-care center outbreaks range from 21 to 44% in the U.S. and from 8 to 27% in Canada.[17] The highest infection rates are usually observed in children who wear diapers (one to three years of age). In a study of 18 randomly selected day-care centers in Atlanta, 10% of diapered children were found infected.[18] Transmission from this age group to older children, day-care staff, and household contacts is also common. About 20% of parents caring for an infected child becomes infected.

Local health officials and managers or water utility companies need to realize that sources of *Giardia* infection other than municipal drinking water exist. Armed with this knowledge, they are less likely to make a quick (and sometimes wrong) assumption that a cluster of recently diagnosed cases in a city is related to municipal drinking water. Drinking water must not be ruled out as a source of infection when a larger than expected number of cases is recognized in a community. However, the possibility that the cases are associated with a day-care center outbreak, drinking untreated stream water, or international travel should also be entertained.

To understand the finer aspects of *Giardia* transmission and strategies for control, the drinking water practitioner must become familiar with several aspects of the parasite's biology. Two forms of the parasite exist: a trophozoite and a cyst, both of which are much larger than bacteria (see Figure 11.8). Trophozoites live in the upper small intestine where they attach to the intestinal wall by means of a disc-shaped suction pad on their ventral surface. Trophozoites actively feed and reproduce at this location. At some time during the trophozoite's life, it releases its hold on the bowel wall and floats in the fecal stream through the intestine. As it makes this journey, it undergoes

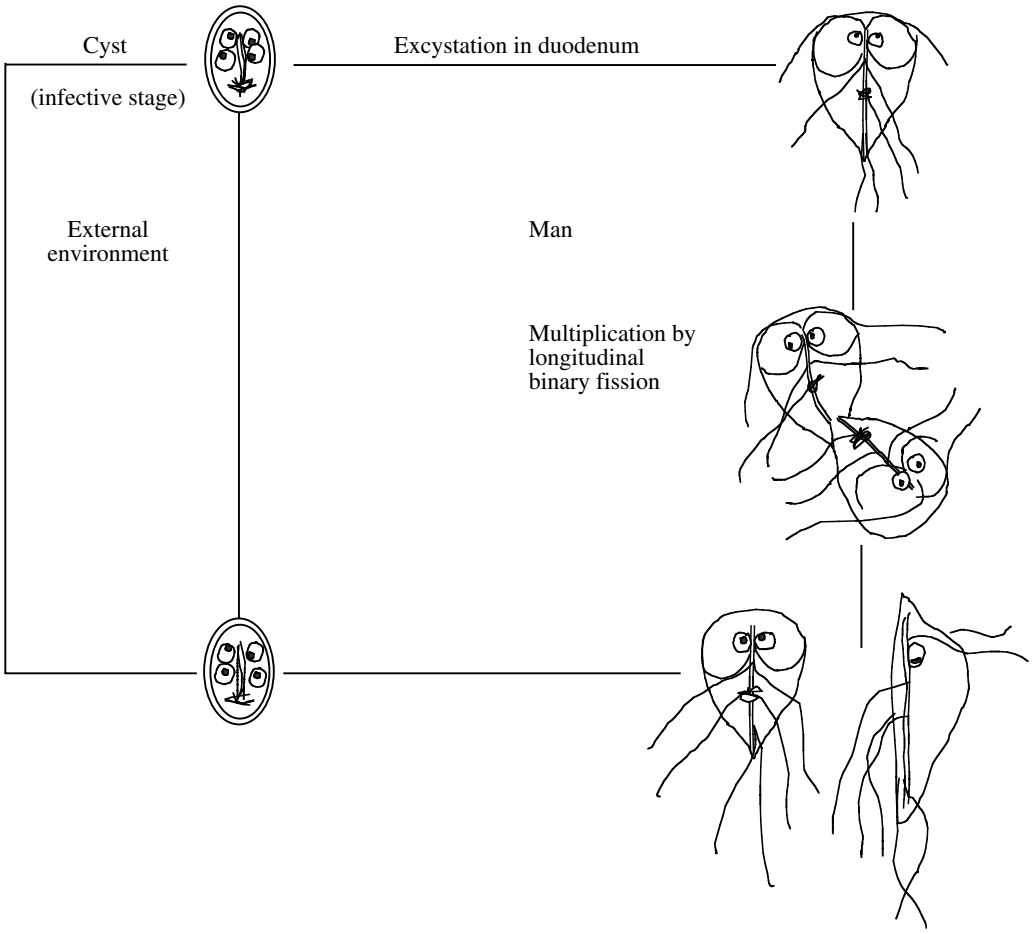

FIGURE 11.8 Life cycle of *Giardia lamblia.* (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

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a morphologic transformation into an egg like structure called a cyst.

The cyst (about 6 to 9 nm in diameter × 8 to 12 μm [1/100 mm] — in length) has a thick exterior wall that protects the parasite against the harsh elements that it will encounter outside the body. This cyst form of parasite is infectious to other people or animals. Most people become infected either directly (by hand-to-mouth transfer of cysts from the feces of an infected individual) or indirectly (by drinking feces-contaminated water). Less common modes of transmission include ingestion of fecally contaminated food and hand-to-mouth transfer of cysts after touching a fecally contaminated surface. After the cyst is swallowed, the trophozoite is liberated through the action of stomach acid and digestive enzymes and becomes established in the small intestine.

Although infection after ingestion of only one *Giardia* cyst is theoretically possible, the minimum number of cysts shown to infect a human under experimental conditions is 10.[19] Trophozoites divide by binary fission about every 12 hours. What this means in practical terms is that if a person swallowed only a single cyst, reproduction at this rate would result in more than 1 million parasites 10 days later, and 1 billion parasites by day 15.

The exact mechanism by which *Giardia* causes illness is not yet well understood, but is not necessarily related to the number of organisms present. Nearly all of the symptoms, however, are related to dysfunction of the gastrointestinal tract. The parasite rarely invades other parts of the body, such as the gall bladder or pancreatic ducts. Intestinal infection does not result in permanent damage.

Note: *Giardia* has an incubation period of 1 to 8 weeks.

Data reported by the CDC indicate that *Giardia* is the most frequently identified cause of diarrheal outbreaks associated with drinking water in the U.S.. The remainder of this section is devoted specifically to waterborne transmissions of *Giardia. Giardia* cysts have been detected in 16% of potable water supplies (lakes, reservoirs, rivers, springs, groundwater) in the U.S. at an average concentration of 3 cysts per 100 L.[20] Waterborne epidemics of giardiasis are a relatively frequent occurrence. In 1983, for example, *Giardia* was identified as the cause of diarrhea in 68% of waterborne outbreaks in which the causal agent was identified.[21] From 1965 to 1982, more than 50 waterborne outbreaks were reported.[22] In 1984, about 250,000 people in Pennsylvania were advised to boil drinking water for six months because of *Giardia*-contaminated water.

Many of the municipal waterborne outbreaks of *Giardia* have been subjected to intense study to determine their cause. Several general conclusions can be made from data obtained in those studies. Waterborne transmission of *Giardia* in the U.S. usually occurs in mountainous regions where community drinking water obtained from clear running streams is chlorinated but not filtered before distribution. Although mountain streams appear to be clean, fecal contamination upstream by human residents or visitors, as well as by *Giardia*-infected animals such as beavers, has been well documented. Water obtained from deep wells is an unlikely source of *Giardia* because of the natural filtration of water as it percolates through the soil to reach underground cisterns. Well-waste sources that pose the greatest risk of fecal contamination are poorly constructed or improperly located ones. A few outbreaks have occurred in towns that included filtration in the water treatment process, where the filtration was not effective in removing *Giardia* cysts because of defects in filter construction, poor maintenance of the filter media, or inadequate pretreatment of the water before filtration. Occasional outbreaks have also occurred because of accidental cross-connections between water and sewage systems.

From these data, we conclude that two major ingredients are necessary for waterborne outbreak. *Giardia* cysts must be present in untreated source water, and the water purification process must either fail to kill or to remove *Giardia* cysts from the water.

Though beavers are often blamed for contaminating water with *Giardia* cysts, that they are responsible for introducing the parasite into new areas seem unlikely. Far more likely is that they are also victims: *Giardia* cysts may be carried in untreated human sewage discharged into the water by small-town sewage disposal plants or originate from cabin toilets that drain directly into streams and rivers. Backpackers, campers, and sports enthusiasts may also deposit *Giardia*-contaminated feces in the environment, which are subsequently washed into streams by rain. In support of this concept is a growing amount of data that indicate a higher *Giardia* infection rate in beavers living downstream from U.S. National Forest campgrounds, compared with a near zero rate of infection in beavers living in more remote areas.

Although beavers may be unwitting victims of the *Giardia* story, they still play an important part in the contamination scheme, because they can (and probably do) serve as amplifying hosts. An amplifying host is one that is easy to infect, serves as a good habitat for the parasite to reproduce, and in the case of *Giardia*, returns millions of cysts to the water for every one ingested. Beavers are especially important in this regard, because they tend to defecate in or very near the water, ensuring that most of the *Giardia* cysts excreted are returned to the water.

The microbial quality of water resources and the management of the microbially laden wastes generated by the burgeoning animal agriculture industry are critical local, regional, and national problems. Animals wastes from cattle, hogs, sheep, horses, poultry, and other livestock and commercial animals can contain high concentrations of

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microorganism, such as *Giardia*, that are pathogenic to humans.

The contribution of other animals to waterborne outbreaks of *Giardia* is less clear. Muskrats (another semi-aquatic animal) have been found in several parts of the U.S. to have high infection rates (30 to 40%).[23] Recent studies have shown that muskrats can be infected with *Giardia* cysts from humans and beavers. Occasional *Giardia* infections have been reported in coyotes, deer, elk, cattle, dogs, and cats (but not in horses and sheep) encountered in mountainous regions of the U.S.. Naturally occurring *Giardia* infections have not been found in most other wild animals (bear, nutria, rabbit, squirrel, badger, marmot, skunk, ferret, porcupine, mink, raccoon, river otter, bobcat, lynx, moose, bighorn sheep).[24]

Scientific knowledge about what is required to kill or remove *Giardia* cysts from a contaminated water supply has increased considerably. For example, we know that cysts can survive in cold water (4ºC) for at least 2 months, and they are killed instantaneously by boiling water (100ºC).[25] We do not know how long the cysts will remain viable at other water temperatures (e.g., at 0ºC or in a canteen at 15 to 20ºC), nor do we know how long the parasite will survive on various environment surfaces (e.g., under a pine tree, in the sun, on a diaper-changing table, or in carpets in a day-care center).

The effect of chemical disinfection (e.g., chlorination) on the viability of *Giardia* cysts is an even more complex issue. The number of waterborne outbreaks of *Giardia* that have occurred in communities where chlorination was employed as a disinfectant-process demonstrates that the amount of chlorine used routinely for municipal water treatment is not effective against *Giardia* cysts. These observations have been confirmed in the laboratory under experimental conditions.[26] This does not mean that chlorine does not work at all. It does work under certain favorable conditions. Without getting too technical, gaining some appreciation of the problem can be achieved by understanding a few of the variables that influence the efficacy of chlorine as a disinfectant.

1. Water pH: at pH values above 7.5, the disinfectant capability of chlorine is greatly reduced.
2. Water temperature: the warmer the water, the higher the efficacy. Chlorine does not work in ice-cold water from mountain streams.
3. Organic content of the water: mud, decayed vegetation, or other suspended organic debris in water chemically combines with chlorine, making it unavailable as a disinfectant.
4. Chlorine contact time: the longer *Giardia* cysts are exposed to chlorine, the more likely the chemical will kill them.
5. Chlorine concentration: the higher the chlorine concentration, the more likely chlorine will kill *Giardia* cysts. Most water treatment facilities try to add enough chlorine to give a free (unbound) chlorine residual at the customer tap of 0.5 mg/L of water.

The five variables above are so closely interrelated that improving another can often compensate for an unfavorable occurrence in one. For example, if chlorine efficacy is expected to be low because water is obtained from an icy stream, the chlorine contact time, chlorine concentration, or both could be increased. In the case of *Giardia*-contaminated water, producing safe drinking water with a chlorine concentration of 1 mg/L and contact time as short as 10 min might be possible if all the other variables were optimal (i.e., pH of 7.0, water temperature of 25ºC, and a total organic content of the water close to zero). On the other hand, if all of these variables were unfavorable (i.e., pH of 7.9, water temperature of 5ºC, and high organic content), chlorine concentrations in excess of 8 mg/L with several hours of contact time may not be consistently effective.

Because water conditions and water treatment plant operations (especially those related to water retention time, and therefore, to chlorine contact time) vary considerably in different parts of the U.S., neither the EPA nor the CDC has been able to identify a chlorine concentration that would be safe yet effective against *Giardia* cysts under all water conditions. Therefore, the use of chlorine as a preventive measure against waterborne giardiasis generally has been used under outbreak conditions when the amount of chlorine and contact time have been tailored to fit specific water conditions and the existing operational design of the water utility.

In an outbreak, for example, the local health department and water utility may issue an advisory to boil water, may increase the chlorine residual at the consumer's tap from 0.5 to 1 or 2 mg/L, and if the physical layout and operation of the water treatment facility permit, increase the chlorine contact time. These are emergency procedures intended to reduce the risk of transmission until a filtration device can be installed or repaired or until an alternative source of safe water (e.g., a well) can be made operational.

The long-term solution to the problem of municipal waterborne outbreaks of giardiasis involves improvements in and more widespread use of filters in the municipal water treatment process. The sand filters most commonly used in municipal water treatment today cost millions of dollars to install, which makes them unattractive for many small communities. The pore sizes in these filters are not sufficiently small to remove a *Giardia* ($6–9 \times 8–12$ μm). For the sand filter to remove *Giardia* cysts from the water effectively, the water must receive some additional treatment before it reaches the filter. The flow of water through the filter bed must also be carefully regulated.

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An ideal prefilter treatment for muddy water would include sedimentation (a holding pond where large suspended particles are allowed to settle out by the action of gravity) followed by flocculation or coagulation (the addition of chemicals, such as alum or ammonium, to cause microscopic particles to clump together). The sand filter easily removes the large particles resulting from the flocculation/coagulation process, including *Giardia* cysts bound to other microparticulates. Chlorine is then added to kill the bacteria and viruses that may escape the filtration process. If the water comes from a relatively clear source, chlorine may be added to the water before it reaches the filter.

The successful operation of a complete waterworks operation is a complex process that requires considerable training. Troubleshooting breakdowns or recognizing the potential problems in the system before they occur often requires the skills of an engineer. Unfortunately, most small water utilities with water treatment facilities that include filtration cannot afford the services of a full-time engineer. Filter operation or maintenance problems in such systems may not be detected until a *Giardia* outbreak is recognized in the community. The bottom line is that although filtration is the best that water treatment technology has to offer for municipal water systems against waterborne giardiasis, it is not infallible. For municipal water filtration facilities to work properly, they must be properly constructed, operated, and maintained.

Whenever possible, persons in the outdoors should carry drinking water of known purity with them. When this is not practical, when water from streams, lakes, ponds, and other outdoor sources must be used, time should be taken to properly disinfect the water before drinking it.

11.11.1.2 *Cryptosporidium*

Ernest E. Tyzzer first described the protozoan parasite *Cryptosporidium* in 1907. Tyzzer frequently found a parasite in the gastric glands of laboratory mice. Tyzzer identified the parasite as a sporozoan, but of uncertain taxonomic status; he named it *Cryptosporidium muris.* Later, in 1910, after more detailed study, he proposed *Cryptosporidium* as a new genus and *C. muris* as the type of species. Amazingly, except for developmental stages, Tyzzer's original description of the life cycle (see Figure 11.9) was later confirmed by electron microscopy. Later, in 1912, Tyzzer described a new species, *Cryptosporidium parvum.*[27]

For almost 50 years, Tyzzer's discovery of the genus *Cryptosporidium* (because it appeared to be of no medical or economic importance) remained (like himself) relatively obscure. However, slight rumblings of the genus' importance were felt in the medical community when

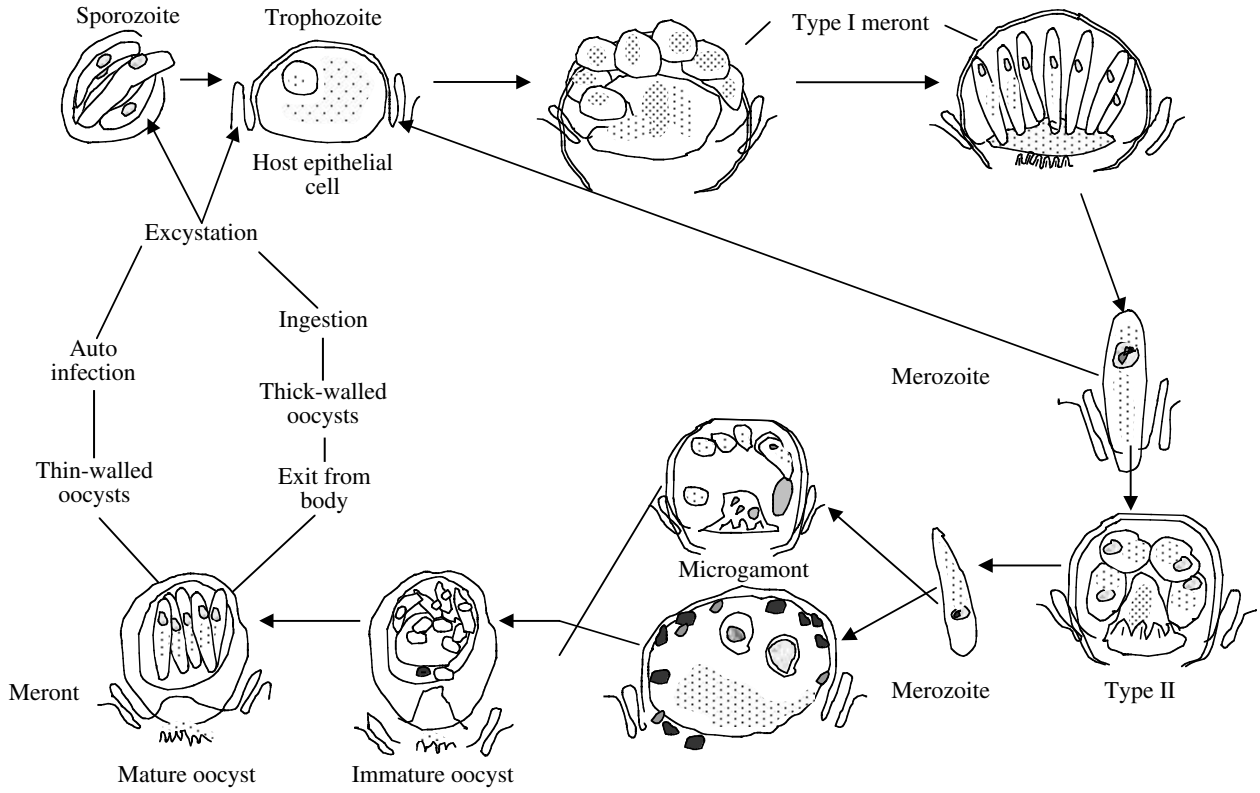

FIGURE 11.9 Life cycle of *Cryptosporiudium parvum.* (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

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Slavin wrote about a new species, *Cryptosporidium meleagridis*, associated with illness and death in turkeys.[28] Interest remained slight even when *Cryptosporidium* was found to be associated with bovine diarrhea.[29]

Not until 1982 did worldwide interest focus in on the study of organisms in the genus *Cryptosporidium.* During this period, the medical community and other interested parties were beginning to attempt a full-scale, frantic effort to find out as much as possible about Acquired Immune Deficiency Syndrome (AIDS). The CDC reported that 21 AIDS-infected males from six large cities in the U.S. had severe protracted diarrhea caused by *Cryptosporidium.*

However, 1993 was when the "bug — the pernicious parasite *Cryptosporidium* — made [itself and] Milwaukee famous."[30]

Note: The *Cryptosporidium* outbreak in Milwaukee caused the deaths of 100 people — the largest episode of waterborne disease in the U.S. in the 70 years since health officials began tracking such outbreaks.

Today we know that the massive waterborne outbreak in Milwaukee (more than 400,000 persons developed acute and often prolonged diarrhea or other gastrointestinal symptoms) increased interest in *Cryptosporidium* at an exponential level. The Milwaukee incident spurred both public interest and the interest of public health agencies, agricultural agencies and groups, environmental agencies and groups, and suppliers of drinking water. This increase in interest level and concern has spurred on new studies of *Cryptosporidium* with emphasis on developing methods for recovery, detection, prevention, and treatment.[31]

The EPA has become particularly interested in this new pathogen. For example, in the reexamination of regulations on water treatment and disinfection, the EPA issued maximum contaminant level goals and contaminant candidate lists for *Cryptosporidium.* The similarity to *Giardia lamblia* and the necessity to provide an efficient conventional water treatment capable of eliminating viruses at the same time forced the USEPA to regulate the surface water supplies in particular. The proposed ESWTR included regulations from watershed protection to specialized operation of treatment plants (certification of operators and state overview) and effective chlorination. Protection against *Cryptosporidium* included control of waterborne pathogens such as *Giardia* and viruses.[32]

11.11.1.2.1 The Basics of Cryptosporidium

*Cryptosporidium (*crip-toe-spor-ID-ee-um) is one of several single-celled protozoan genera in the phylum Apircomplexa (all referred to as coccidian). *Cryptosporidium*, along with other genera in the phylum Apircomplexa, develop in the gastrointestinal tract of vertebrates through all of their life cycle — in short, they live in the intestines of animals and people. This microscopic pathogen causes a disease called cryptosporidiosis (crip-toe-spor-id-ee-O-sis).

TABLE 11.3
Valid Named Species of *Cryptosporidium*[33]

Species	Host
C. baileyi	Chicken
C. felis	Domestic cat
C. meleagridis	Turkey
C. murishouse	House mouse
C. nasorium	Fish
C. parvum	House mouse
C. serpentis	Corn snake
C. wrairi	Guinea pig

Source: From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revsed ed.), Technomic Publ., Lancaster, PA, 2000.

The dormant (inactive) form of *Cryptosporidium* called an oocyst (O-o-sist) is excreted in the feces (stool) of infected humans and animals. The tough-walled oocysts survive under a wide range of environmental conditions.

Several species of *Cryptosporidium* were incorrectly named after the host in which they were found; subsequent studies have invalidated many species. Now, eight valid species of *Cryptosporidium* (see Table 11.3) have been named.

Upton[32a] reports that *C. muris* infects the gastric glands of laboratory rodents and several other mammalian species, but (even though several texts state otherwise) is not known to infect humans, However, *C. parvum* infects the small intestine of an unusually wide range of mammals, including humans, and is the zoonotic species responsible for human cryptosporidiosis. In most mammals *C. parvum* is predominately a parasite of neonate (newborn) animals. He points out that even though exceptions occur, older animals generally develop poor infections, even when unexposed previously to the parasite. Humans are the one host that can be seriously infected at any time in their lives, and only previous exposure to the parasite results in either full or partial immunity to challenge infections.

Oocysts are present in most surface bodies of water across the U.S., many of which supply public drinking water. Oocysts are more prevalent in surface waters when heavy rains increase runoff of wild and domestic animal wastes from the land, or when sewage treatment plants are overloaded or break down.

Only laboratories with specialized capabilities can detect the presence of *Cryptosporidium* oocysts in water. Unfortunately, present sampling and detection methods are unreliable. Recovering oocysts trapped on the material

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used to filter water samples is difficult. Once a sample is obtained, however, determining whether the oocyst is alive or whether it is the species *C. parvum* that can infect humans is easily accomplished by looking at the sample under a microscope.

The number of oocysts detected in raw (untreated) water varies with location, sampling time, and laboratory methods. Water treatment plants remove most, but not always all, oocysts. Low numbers of oocysts are sufficient to cause cryptosporidiosis, but the low numbers of oocysts sometimes present in drinking water are not considered cause for alarm in the public.

Protecting water supplies from *Cryptosporidium* demands multiple barriers. Why? Because *Cryptosporidium* oocysts have tough walls that can withstand many environmental stresses and are resistant to the chemical disinfectants such as chlorine that are traditionally used in municipal drinking water systems.

Physical removal of particles, including oocysts, from water by filtration is an important step in the water treatment process. Typically, water pumped from rivers or lakes into a treatment plant is mixed with coagulants that help settle out particles suspended in the water. If sand filtration is used, even more particles are removed. Finally, the clarified water is disinfected and piped to customers. Filtration is the only conventional method now in use in the U.S. for controlling *Cryptosporidium*.

Ozone is a strong disinfectant that kills protozoa if sufficient doses and contact times are used, but ozone leaves no residual for killing microorganisms in the distribution system, as does chlorine. The high costs of new filtration or ozone treatment plants must be weighed against the benefits of additional treatment. Even well operated water treatment plants cannot ensure that drinking water will be completely free of *Cryptosporidium* oocysts. Water treatment methods alone cannot solve the problem; watershed protection and monitoring of water quality are critical.

As mentioned, watershed protection is another barrier to *Cryptosporidium* in drinking water. Land use controls such as septic systems regulations and best management practices to control runoff can help keep human and animal wastes out of water.

Under the SWTR of 1989, public water systems must filter surface water sources unless water quality and disinfection requirements are met and a watershed control program is maintained. This rule, however, did not address *Cryptosporidium.* The EPA has now set standards for turbidity (cloudiness) and coliform bacteria (which indicate that pathogens are probably present) in drinking water. Frequent monitoring must occur to provide officials with early warning of potential problems to enable them to take steps to protect public health. Unfortunately, no water quality indicators can reliably predict the occurrence of cryptosporidiosis. More accurate and rapid assays of oocysts will make it possible to notify residents promptly if their water supply is contaminated with *Cryptosporidium* and thus avert outbreaks.

The bottom line is that the collaborative efforts of water utilities, government agencies, health care providers, and individuals are needed to prevent outbreaks of cryptosporidiosis.

11.11.1.2.2 Cryptosporidiosis

Denis D. Juranek from the CDC has written in *Clinical Infectious Diseases:*

> *Cryptosporidium parvum* is an important emerging pathogen in the U.S. and a cause of severe, life-threatening disease in patients with AIDS. No safe and effective form of specific treatment for Cryptosporidiosis has been identified to date. The parasite is transmitted by ingestion of oocysts excreted in the feces of infected humans or animals. The infection can therefore be transmitted from person-to-person, through ingestion of contaminated water (drinking water and water used for recreational purposes) or food, from animal to person, or by contact with fecally contaminated environmental surfaces. Outbreaks associated with all of these modes of transmission have been documented. Patients with human immunodeficiency virus infection should be made more aware of the many ways that *Cryptosporidium* species are transmitted, and they should be given guidance on how to reduce their risk of exposure.[34]

The CDC points out that since the Milwaukee outbreak, concern about the safety of drinking water in the U.S. has increased, and new attention has been focused on determining and reducing the risk of cryptosporidiosis from community and municipal water supplies.

Cryptosporidiosis is spread by putting something in the mouth that has been contaminated with the stool of an infected person or animal. In this way, people swallow the *Cryptosporidium* parasite. As previously mentioned, a person can become infected by drinking contaminated water or eating raw or undercooked food contaminated with *Cryptosporidium* oocysts, coming into direct contact with the droppings of infected animals or stools of infected humans, or having hand-to-mouth transfer of oocysts from surfaces that may have become contaminated with microscopic amounts of stool from an infected person or animal.

The symptoms may appear 2 to 10 days after infection by the parasite. Although some persons may not have symptoms, others have watery diarrhea, headache, abdominal cramps, nausea, vomiting, and low-grade fever. These symptoms may lead to weight loss and dehydration.

In otherwise healthy persons, these symptoms usually last 1 to 2 weeks, at which time the immune system is able to stop the infection. In persons with suppressed immune systems, such as persons who have AIDS or who

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recently have had an organ or bone marrow transplant, the infection may continue and become life threatening.

There is no safe and effective cure for cryptosporidiosis. People with normal immune systems improve without taking antibiotic or antiparasitic medications. The treatment recommend for this diarrheal illness is to drink plenty of fluids and to get extra rest. Physicians may prescribe medication to slow the diarrhea during recovery.

The best way to prevent cryptosporidiosis is:

1. Avoid water or food that may be contaminated.
2. Wash hands after using the toilet and before handling food.
3. If you work in a childcare center where you change diapers, be sure to wash your hands thoroughly with plenty of soap and warm water after every diaper change, even if you wear gloves.

During community-wide outbreaks caused by contaminated drinking water, drinking water practitioners should inform the public to boil drinking water for one minute to kill the *Cryptosporidium* parasite.

11.11.1.3 *Cyclospora*

Cyclospora organisms, which until recently were considered blue-green algae, were discovered at the turn of the century. The first human cases of *Cyclospora* infection were reported in the 1970s. In the early 1980s, *Cyclospora* was recognized as pathogen in patients with AIDS. We now know that *Cyclospora* is endemic in many parts of the world, and appears to be an important cause of traveler's diarrhea. *Cyclospora* are 2 to 3 times larger than *Cryptosporidium*, but otherwise have similar features. *Cyclospora* diarrheal illness in patients with healthy immune systems can be cured with a week of therapy with timethoprim-sulfamethoxazole.

Exactly what is *Cyclospora*? In 1998, the CDC described *Cyclospora cayetanesis* as a unicellular parasite previously known as a cyanobacterium-like (blue-green algae-like) or coccidian-like body. The disease is known as cyclosporiasis. *Cyclospora* infects the small intestine and causes an illness characterized by diarrhea with frequent stools. Other symptoms can include loss of appetite, bloating, gas, stomach cramps, nausea, vomiting, fatigue, muscle ache, and fever. Some individuals infected with *Cyclospora* may not show symptoms. Since the first known cases of illness caused by *Cyclospora* infection were reported in the medical journals in the 1970s, cases have been reported with increased frequency from various countries since the mid-1980s (in part because of the availability of better techniques for detecting the parasite in stool specimens).

Huang et al. detailed what they believe is the first known outbreak of diarrheal illness associated with *Cyclospora* in the U.S. The outbreak, which occurred in 1990, consisted of 21 cases of illness among physicians and others working at a Chicago hospital. Contaminated tap water from a physicians' dormitory at the hospital was the probable source of the organisms. The tap water probably picked up the organism while in a storage tank at the top of the dormitory after the failure of a water pump.[35]

The transmission of *Cyclospora* is not a straightforward process. When infected persons excrete the oocyst state of *Cyclospora* in their feces, the oocysts are not infectious and may require from days to weeks to become so (i.e., to sporulate). Therefore, transmission of *Cyclospora* directly from an infected person to someone else is unlikely. Indirect transmission can occur if an infected person contaminates the environment and oocysts have sufficient time, under appropriate conditions, to become infectious. For example, *Cyclospora* may be transmitted by ingestion of water or food contaminated with oocysts. Outbreaks linked to contaminated water, as well as outbreaks linked to various types of fresh produce, have been reported in recent years.[36] How common the various modes of transmission and sources of infection are is not yet known, nor is it known whether animals can be infected and serve as sources of infection for humans.

Note: *Cyclospora* organisms have not yet been grown in tissue cultures or laboratory animal models.

Persons of all ages are at risk for infection. Persons living or traveling in developing countries may be at increased risk, but infection can be acquired worldwide, including in the U.S. In some countries of the world, infection appears to be seasonal.

Based on currently available information, avoiding water or food that may be contaminated with stool is the best way to prevent infection. Reinfection can occur.

Note: De Zuane points out that pathogenic parasites are not easily removed or eliminated by conventional treatment and disinfection unit processes. This is particularly true for *Giardia lamblia, Cryptosporidium,* and *Cyclospora.* Filtration facilities can be adjusted in depth, prechlorination, filtration rate, and backwashing to become more effective in the removal of cysts. The pretreatment of protected water shed raw water is a major factor in the elimination of pathogenic protozoa.

11.11.2 Helminths

Helminthes are parasitic worms that grow and multiply in sewage (biological slimes) and wet soil (mud). They multiply in wastewater treatment plants. Strict aerobes, they have been found in activated sludge and particularly in

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trickling filters, and therefore appear in large concentrations in treated domestic liquid waste. They enter the skin or by ingestion of the worm in one of its many life cycle phases. Generally, they are not a problem in drinking water supplies in the U.S. because both their egg and larval forms are large enough to be trapped during conventional water treatment. In addition, most Helminthes are not waterborne, so chances of infection are minimized.[38]

11.12 BIOLOGICAL ASPECTS AND PROCESSES (WASTEWATER)

Uncontrolled bacteria in industrial water systems produce an endless variety of problems including disease, equipment damage, and product damage. Unlike the microbiological problems that can occur in water systems, in wastewater treatment, microbiology can be applied as a beneficial science for the destruction of pollutants in wastewater.[39]

It should be noted that all the biological processes used for the treatment of wastewater (in particular) are derived or modeled from processes occurring naturally in nature. The processes discussed in the following are typical examples. It also should be noted, as Metcalf & Eddy, Inc., point out, "that by controlling the environment of microorganisms, the decomposition of wastes is speeded up. Regardless of the type of waste, the biological treatment process consists of controlling the environment required for optimum growth of the microorganism involved."[40]

11.12.1 Aerobic Process

In aerobic treatment processes, organisms use free, elemental oxygen and organic matter together with nutrients (nitrogen, phosphorus) and trace metals (iron, etc.) to produce more organisms and stable dissolved and suspended solids and carbon dioxide (see Figure 11.10).

11.12.2 Anaerobic Process

The *anaerobic treatment process* consists of two steps, occurs completely in the absence of oxygen, and produces a useable by-product: methane gas.

In the first step of the process, facultative microorganisms use the organic matter as food to produce more organisms, volatile (organic) acids, carbon dioxide, hydrogen sulfide, and other gases and some stable solids (see Figure 11.11).

In the second step, anaerobic microorganisms use the volatile acids as their food source. The process produces more organisms, stable solids, and methane gas that can be used to provide energy for various treatment system components (see Figure 11.12).

Oxygen		More bacteria
Bacteria	⇒	Stable solids
Organic matter		Settleable solids
Nutrients		Carbon dioxide

FIGURE 11.10 Aerobic decomposition. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

Facultative bacteria		More bacteria
Organic matter	⇒	Volatile solids
Nutrients		Settleable solids
		Hydrogen sulfide

FIGURE 11.11 Anaerobic decomposition — first step. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

Anaerobic bacteria		More bacteria
Volatile acids	⇒	Stable solids
Nutrients		Settleable solids
		Methane

FIGURE 11.12 Anaerobic decomposition — second step. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

Nitrate oxygen		More bacteria
Bacteria		Stable solids
Organic matter	⇒	Settleable solids
Nutrients		Nitrogen

FIGURE 11.13 Anoxic decomposition. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

11.12.3 Anoxic Process

In the anoxic treatment process (anoxic means without oxygen), microorganisms use the fixed oxygen in nitrate compounds as a source of energy. The process produces more organisms and removes nitrogen from the wastewater by converting it to nitrogen gas that is released into the air (see Figure 11.13).

11.12.4 Photosynthesis

Green algae use carbon dioxide and nutrients in the presence of sunlight and chlorophyll to produce more algae and oxygen (see Figure 11.14).

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Sun		
Algae	⇒	More algae
Carbon dioxide		Oxygen
Nutrients		

FIGURE 11.14 Photosynthesis. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

11.12.5 Growth Cycles

All organisms follow a basic growth cycle that can be shown as a growth curve. This curve occurs when the environmental conditions required for the particular organism are reached. It is the environmental conditions (i.e., oxygen availability, pH, temperature, presence or absence of nutrients, presence or absence of toxic materials) that determine when a particular group of organisms will predominate. This information can be very useful in operating a biological treatment process (see Figure 11.15).

11.12.6 Biogeochemical Cycles

Several chemicals are essential to life and follow predictable cycles through nature. In these natural cycles, or biogeochemical cycles, the chemicals are converted from one form to another as they progress through the environment. Water and wastewater operators should be aware of those cycles dealing with the nutrients (e.g., carbon, nitrogen, and sulfur) because they have a major impact on the performance of the plant and may require changes in operation at various times of the year to keep them functioning properly; this is especially the case in wastewater treatment. The microbiology of each cycle deals with the biotransformation and subsequent biological removal of these nutrients in wastewater treatment plants.

Note: Smith categorizes biogeochemical cycles into two types, the gaseous and the sedimentary. Gaseous cycles include the carbon and nitrogen cycles. The main sink of nutrients in the gaseous cycle is the atmosphere and the ocean. Sedimentary cycles include the sulfur and phosphorus cycle. The main sink for sedimentary cycles is soil and rocks of the earth's crust.[41]

11.12.6.1 Carbon Cycle

Carbon, an essential ingredient of all living things, is the basic building block of the large organic molecules necessary for life. Carbon is cycled into food chains from the atmosphere, as shown in Figure 11.16.

From Figure 11.16 it can be seen that green plants obtain carbon dioxide (CO_2) from the air and, through photosynthesis, described by Asimov as the "most important chemical process on Earth," it produces the food and oxygen that all organisms live on.[42] Part of the carbon produced remains in living matter; the other part is released as CO_2 in cellular respiration. Miller points out that the CO_2 released by cellular respiration in all living organisms is returned to the atmosphere.[43]

Some carbon is contained in buried dead and animal and plant materials. Much of these buried animal and plant materials were transformed into fossil fuels. Fossil fuels, coal, oil, and natural gas, contain large amounts of carbon. When fossil fuels are burned, stored carbon combines with oxygen in the air to form CO_2, which enters the atmosphere.

In the atmosphere, CO_2 acts as a beneficial heat screen as it does not allow the radiation of earth's heat into space. This balance is important. The problem is that as more carbon dioxide from burning is released into the atmosphere, the balance can and is being altered. Odum warns that the recent increase in consumption of fossil fuels "coupled with the decrease in 'removal capacity' of the green belt is beginning to exceed the delicate balance."[44] Massive

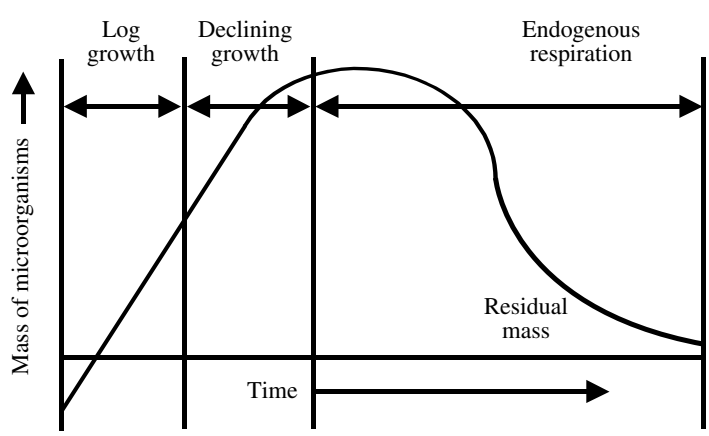

FIGURE 11.15 Microorganism growth curve. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

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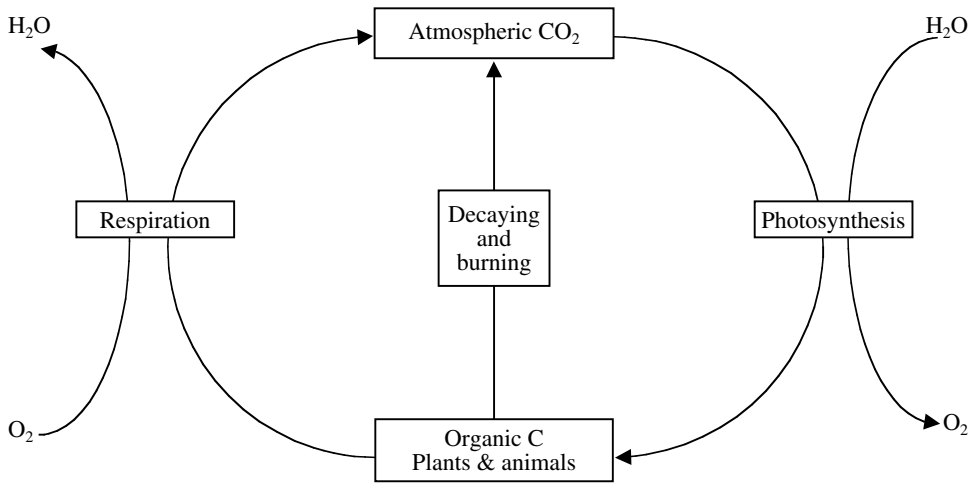

FIGURE 11.16 Carbon cycle. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

increases of carbon dioxide into the atmosphere tend to increase the possibility of global warming. The consequences of global warming "would be catastrophic…and the resulting climatic change would be irreversible."[45]

11.12.6.2 Nitrogen Cycle

Nitrogen is an essential element that all organisms need. In animals, nitrogen is a component of crucial organic molecules, such as proteins and DNA, and constitutes 1 to 3% dry weight of cells. Our atmosphere contains 78% by volume of nitrogen, yet it is not a common element on earth. Although nitrogen is an essential ingredient for plant growth, it is chemically very inactive, and before the vast majority of the biomass can incorporate it, it must be fixed. Special nitrogen-fixing bacteria found in soil and water fix nitrogen. Thus, microorganisms play a major role in nitrogen cycling in the environment. These microorganisms (bacteria) have the ability to take nitrogen gas from the air and convert it to nitrate. This is called nitrogen fixation. Some of these bacteria occur as free-living organisms in the soil. Others live in a symbiotic relationship (a close relationship between two organisms of different species, and one where both partners benefit from the association) with plants.

An example of a symbiotic relationship related to nitrogen can be seen in the roots of peas. These roots have small swellings along their length. These contain millions of symbiotic bacteria, that have the ability to take nitrogen gas from the atmosphere and convert it to nitrates that can be used by the plant. Then the plant is plowed into the soil after the growing season to improve the nitrogen content. Price describes the nitrogen cycle as an example "of a largely complete chemical cycle in ecosystems with little leaching out of the system."[46] Simply, the nitrogen cycle provides various bridges between the atmospheric reservoirs and the biological communities (see Figure 11.17).

Atmospheric nitrogen is fixed either by natural or industrial means. For example, nitrogen is fixed by lightning or by soil bacteria that convert it to ammonia, then to nitrite, and finally to nitrates, which plants can use. Nitrifying bacteria make nitrogen from animal wastes. Denitrifying bacteria convert nitrates back to nitrogen and release it as nitrogen gas.

The logical question is: What does all of this have to do with water? The best way to answer this question is to ask another question. Have you ever dived into a slow-moving stream and had the noxious misfortune to surface right in the middle of an algal bloom? When this happens to you, the first thought that runs through your mind is, "Where is my nose plug?" Why? Because of the horrendous stench, disablement of the olfactory sense is a necessity.

If too much nitrate, for example, enters the water supply as runoff from fertilizers, it produces an overabundance of algae called algal bloom. If this runoff from fertilizer gets into a body of water, algae may grow so profusely that they form a blanket over the surface. This usually happens in summer, when the light levels and warm temperatures favor rapid growth.

Metcalf & Eddy, Inc., in their voluminous and authoritative text, *Wastewater Engineering: Treatment, Disposal, and Reuse*, point out that nitrogen is found in wastewater in the form of urea. During wastewater treatment, the urea is transformed into ammonia nitrogen. Since ammonia exerts a BOD and chlorine demand, high quantities of ammonia in wastewater effluents are undesirable. The process of nitrification is utilized to convert ammonia to nitrates. Nitrification is a biological process that involves the addition of oxygen to the wastewater. If further treatment is necessary, another biological process called denitrification is used. In this process, nitrate is converted into

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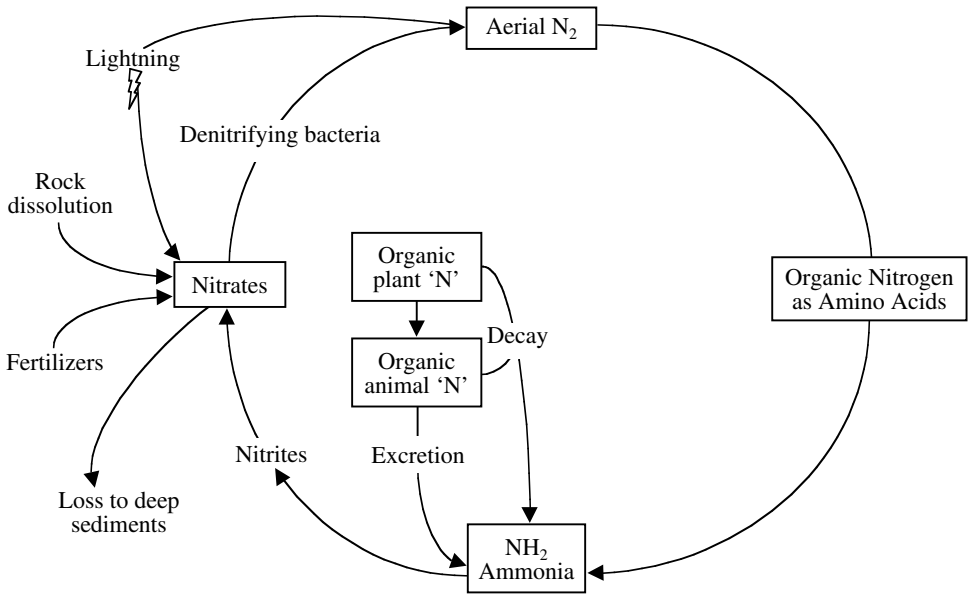

FIGURE 11.17 Nitrogen cycle. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

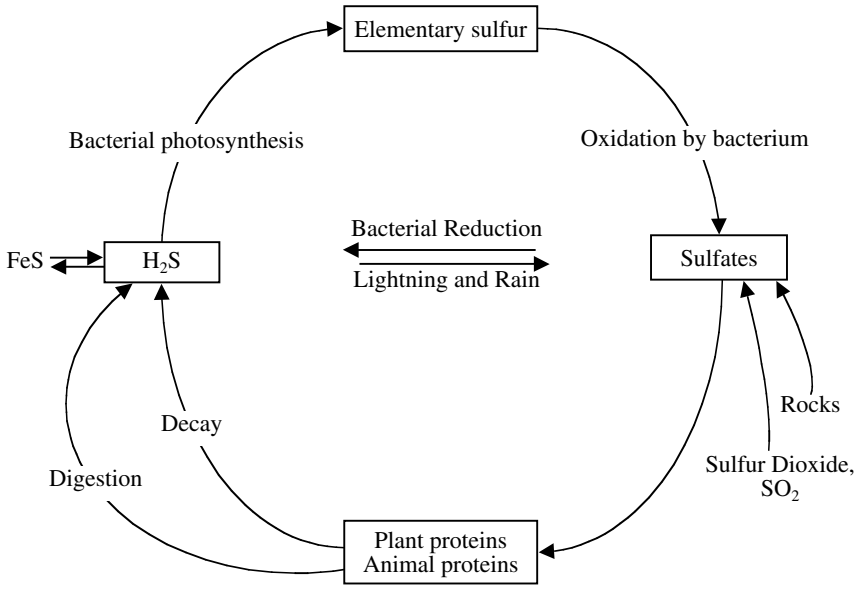

FIGURE 11.18 The sulfur cycle. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

nitrogen gas, which is lost to the atmosphere, as can be seen in Figure 11.18. From the wastewater operator's point of view, nitrogen and phosphorus are both considered limiting factors for productivity. Phosphorus discharged into streams contributes to pollution. Of the two, nitrogen is harder to control, but is found in smaller quantities in wastewater.

11.12.6.3 Sulfur Cycle

Sulfur, like nitrogen, is characteristic of organic compounds. The sulfur cycle is both sedimentary and gaseous (see Figure 11.18). Tchobanoglous and Schroeder note that, "the principal forms of sulfur that are of special significance in water quality management are organic sulfur, hydrogen sulfide, elemental sulfur and sulfate."[47]

Bacteria play a major role in the conversion of sulfur from one form to another. In an anaerobic environment, bacteria break down organic matter and produce hydrogen sulfide with its characteristic rotten-egg odor. A bacterium called *Beggiatoa* converts hydrogen sulfide into elemental sulfur into sulfates. Other sulfates are contributed by the dissolving of rocks and some sulfur dioxide. Sulfur is

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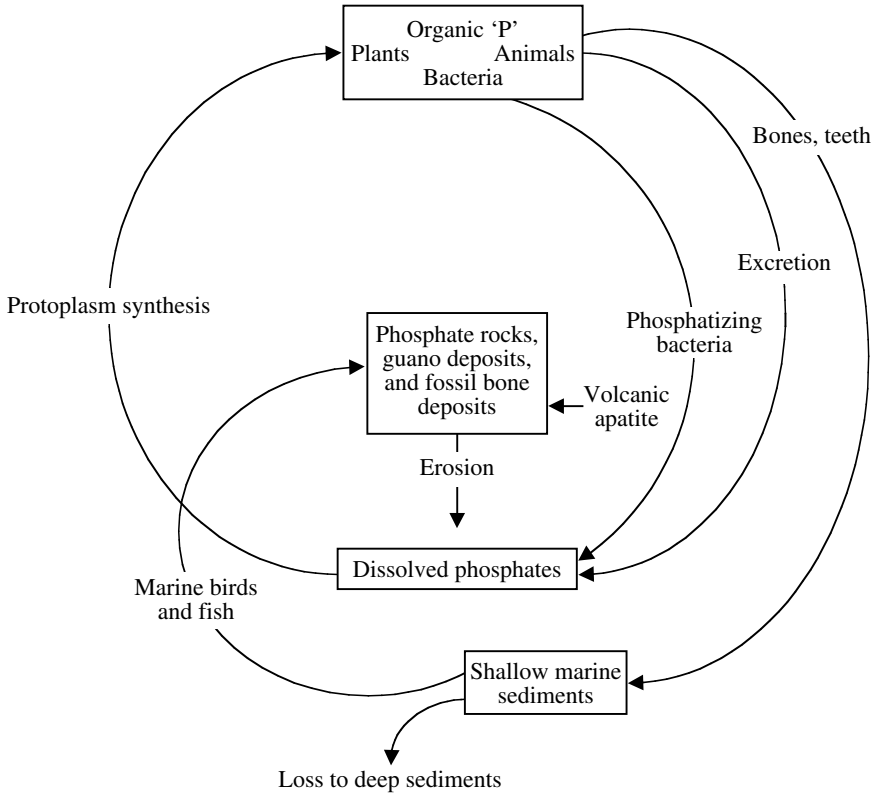

FIGURE 11.19 The phosphorus cycle. (From Spellman, F.R., *Microbiology for Waste/Wastewater Operators* (revised ed.), Technomic Publ., Lancaster, PA, 2000.)

incorporated by plants into proteins. Organisms then consume some of these plants. Many heterotrophic anaerobic bacteria liberate sulfur from proteins as hydrogen sulfide.

11.12.6.4 Phosphorus Cycle

Phosphorus is another chemical element that is common in the structure of living organisms. However, the phosphorus cycle is different from the hydrologic, carbon and nitrogen cycles because phosphorus is found in sedimentary rock, not the atmosphere. In fact, the ultimate source of phosphorus is rock. These massive deposits are gradually eroding to provide phosphorus to ecosystems. A large amount of eroded phosphorus ends up in deep sediments in the oceans and in lesser amounts in shallow sediments. Part of the phosphorus comes to land when marine animals surface. Decomposing plant or animal tissue and animal droppings return organic forms of phosphorus to the water and soil. For example, fish-eating birds play a role in the recovery of phosphorus. The guano deposit, bird excreta, of the Peruvian coast is an example. Humans have hastened the rate of phosphorus loss through mining and the production of fertilizers, which is washed away and lost. Odum points out, however, that even with the increase in human activities, there is no immediate cause for concern, since the known reserves of phosphate are quite large. Figure 11.19 shows the phosphorus cycle.[48]

Phosphorus has become very important in water quality studies, because it is often found to be a limiting factor. Metcalf & Eddy, Inc., reports that control of phosphorus compounds that enter surface waters and contribute to growth of algal blooms is of much interest and has generated much study.[49] Phosphates upon entering a stream act as fertilizer, promoting the growth of undesirable algae populations or algal blooms. As the organic matter decays, DO levels decrease and fish and other aquatic species die.

While it is true that phosphorus discharged into streams is a contributing factor to stream pollution, it is also true that phosphorus is not the lone factor. Odum warns against what he calls the one-factor control hypothesis, (i.e., the one-problem/one-solution syndrome). He notes that environmentalists in the past have focused on one of two items, like phosphorus contamination, and "have failed to understand that the strategy for pollution control must involve reducing the input of all enriching and toxic materials."[50]

11.13 CHAPTER REVIEW QUESTIONS AND PROBLEMS

11.1. Name the three major groups of microorganisms that cause disease in water.

11.2. When does a river of good quality show its highest bacterial numbers?

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11.3. Are coliform organisms pathogenic?
11.4. How do bacteria reproduce?
11.5. Name the three common shapes of bacteria.
11.6. Name three waterborne diseases caused by bacteria.
11.7. Name two protozoa-caused waterborne diseases.
11.8. When a protozoon is in a resting phase, it is called a _____.
11.9. For a virus to live it must have a _____.
11.10. What problems do algae cause in drinking water?
11.11. Do you think freezing will kill bacteria? If not, why not?

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12 Water Ecology

Streams are arteries of earth, beginning in capillary creeks, brooks, and rivulets. No matter the source, they move in only one direction — downhill — the heavy hand of gravity tugs and drags the stream toward the sea. During its inexorable flow downward, now and then there is an abrupt change in geology. Boulders are mowed down by slumping (gravity) from their in place points high up on canyon walls.

As stream flow grinds, chisels, and sculpts the landscape, the effort is increased by momentum, augmented by turbulence provided by rapids, cataracts, and waterfalls. These falling waters always hypnotize us, like fire gazing or wave-watching

Before emptying into the sea, streams often pause, forming lakes. When one stares into a healthy lake, its phantom blue-green eye stares right back. Only for a moment, relatively speaking of course, because all lakes are ephemeral, doomed. Eventually the phantom blue-green eye is close lidded by the moist verdant green of landfill.

For water that escapes the temporary bounds of a lake, most of it evaporates or moves on to the sea.

12.1 INTRODUCTION

This chapter deals primarily with the interrelationship (the ecology) of biota (life forms) in a placid water body (lake) and running water (stream) environment. The bias of this chapter is dictated by our experience and interest and by our belief that there is a need for water and wastewater operators to have a basic knowledge of water-related ecological processes.

Ecology is important because the environmental challenges we face today include all the same ones that we faced more than 30 years ago at the first Earth Day celebration in 1970. In spite of unflagging efforts of environmental professionals (and others), environmental problems remain. Many large metropolitan areas continue to be plagued by smog, our beaches are periodically polluted by oil spills, and many of our running and standing waters (streams and lakes) still suffer the effects of poorly treated sewage and industrial discharges. However, considerable progress has been made. For example, many of our rivers and lakes that were once unpleasant and unhealthy are now fishable and swimmable.

This is not to say that we are out of the woods yet. The problem with making progress in one area is that new problems are discovered that prove to be even more intractable than those we have already encountered. In restoring our running and standing waters to their original pristine state, this has been found to be the case.

Those impacted by the science of freshwater ecology (e.g., water practitioners) must understand the effects of environmental stressors, such as toxics, on the microbiological ecosystem in running and standing waters. Moreover, changes in these ecosystems must be measured and monitored.

As our list of environmental concerns related to standing or running waters grows and the very nature of the problems change, it has been challenging to find materials suitable to train water and wastewater operators as well as students in the classroom. There has never been a shortage of well-written articles for the professional or nonprofessional, and there are now many excellent textbooks that provide cursory, nontechnical, introductory information for undergraduate students. There are also numerous scientific journals and specialized environmental texts for advanced students. Most of these technical publications presuppose a working knowledge of fundamental freshwater ecology principles that a beginning student probably would not have.

The purpose of this chapter is to fill the gap between these general introductory science texts and the more advanced environmental science books used in graduate courses by covering the basics of ecology. Moreover, the necessary fundamental science and water ecology principles that are generally assumed as common knowledge for an advanced undergraduate may be new to or need to be reviewed for water/wastewater operators.

The science of freshwater ecology is a dynamic discipline; new scientific discoveries are made daily and new regulatory requirements are almost as frequent. Today's emphasis is placed on other aspects of freshwater ecology (e.g., nonpoint source pollution and total maximum daily load).

Finally, in the study of freshwater ecology it is important to remember axiom that left to her, Mother Nature can perform wonders, but overload her and there might be hell to pay.

12.2 SETTING THE STAGE

We poison the caddis flies in a stream and the salmon runs dwindle and die. We poison the gnats in a lake and the

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> poison travels from link to link of the food chain and soon the birds of the lake margins become victims. We spray our elms and the following springs are silent of robin song, not because we sprayed the robins directly but because the poison traveled, step by step, through the now familiar elm leaf-earthworm-robin cycle. These are matters of record, observable, part of the visible world around us. They reflect the web of life — or death — that scientists know as ecology.[1]

As Rachel Carson points out, what we do to any part of our environment has an impact upon other parts. There is the interrelationship between the parts that make up our environment. Probably the best way to state this interrelationship is to define ecology. Ecology is the science that deals with the specific interactions that exist between organisms and their living and nonliving environment. The word ecology is derived from the Greek oikos, meaning home. Therefore, ecology is the study of the relation of an organism or a group of organisms to their environment (their home).

Charles Darwin explained ecology in a famous passage in *The Origin of Species* — a passage that helped establish the science of ecology. A "web of complex relations" binds all living things in any region, Darwin writes. Adding or subtracting even single species causes waves of change that race through the web, "onwards in ever-increasing circles of complexity." The simple act of adding cats to an English village would reduce the number of field mice. Killing mice would benefit the bumblebees, whose nest and honeycombs the mice often devour. Increasing the number of bumblebees would benefit the heartsease and red clover, which are fertilized almost exclusively by bumblebees. So adding cats to the village could end by adding flowers. For Darwin the whole of the Galapagos Archipelago argues this fundamental lesson. The volcanoes are much more diverse in their ecology than their biology. The contrast suggests that in the struggle for existence, species are shaped at least as much by the local flora and fauna as by the local soil and climate. "Why else would the plants and animals differ radically among islands that have the same geological nature, the same height, and climate?"[2]

The environment includes everything important to the organism in its surroundings. The organism's environment can be divided into four parts:

1. Habitat and distribution (its place to live)
2. Other organisms (whether friendly or hostile)
3. Food
4. Weather (light, moisture, temperature, soil, etc.

There are two major subdivisions of ecology: autecology and synecology. Autecology is the study of the individual organism or a species. It emphasizes life history, adaptations, and behavior. It is the study of communities, ecosystems, and the biosphere. Synecology is the study of groups of organisms associated together as a unit.

An example of autecology is when biologists spend their entire lifetime studying the ecology of the salmon. Synecology, on the other hand, deals with the environmental problems caused by mankind. For example, the effects of discharging phosphorous-laden effluent into a stream or lake involve several organisms.

There are many other examples of the human impact on natural water systems. For example, consider two common practices from the past. In our first example, a small water-powered lumber mill is located on a steam near town. On a daily basis, the mill reduced tall trees to dimension lumber; it also produced huge piles of sawdust and other wastes. Instead of burning the debris, the mill used the stream to carry the sawdust out of sight. When the heavy fall and winter rains drenched the mill site area, the stream rose and flushed the mill debris down into larger rivers and eventually out to sea. Sawdust covered the river bottoms, smothering and killing the natural food web. When the debris began to rot, it sucked oxygen out of the water. Furthermore, sawdust suspended in the stream clogged the gills of juvenile and adult fish. Eventually evidence of the destructive effects of sawdust in the stream and rivers convinced local lawmakers to act in an attempt to restore the stream and rivers back to their natural state.

Another common practice that contributed to stream and river pollution was gold mining. Mining waste still contributes to stream pollution. However, in the early age of gold strikes in the western U.S., gold miners exacerbated the situation by using hydraulic mining to uncover hidden gold in the hills. Using high-pressure hoses, miners literally disintegrated whole hillsides and washed them into streams and rivers. Streams and rivers ran thick with soil, clogging fish gills, covering natural stream and river bottoms and smothering the insect larvae that higher species consumed.

From these examples, it should be apparent that the activities of human beings (past and present) have become a major component of many natural areas. As a result, it is important to realize that the study of ecology must involve people.

12.3 ECOLOGY TERMS

Each division of ecology has its own set of terms that are essential for communication between ecologists and those who are studying running and standing water ecological systems. Therefore, along with basic ecological terms, key terms that specifically pertain to this chapter are defined and presented in the following section.

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12.3.1 Definition of Terms

Abiotic factor the nonliving part of the environment composed of sunlight, soil, mineral elements, moisture, temperature, and topography.

Aeration a process whereby water and air or oxygen are mixed.

Autotrophic (primary producer) any green plant that fixes energy of sunlight to manufacture food from inorganic substances.

Bacteria among the most common microorganisms in water. Bacteria are primitive, single-celled organisms with a variety of shapes and nutritional needs.

Biochemical oxygen demand (BOD) a widely used parameter of organic pollution applied to both wastewater and surface water … involving the measurement of the dissolved oxygen used by microorganisms in the biochemical oxidation of organic matter.

Biotic factor (community) the living part of the environment composed of organisms that share the same area; are mutually sustaining; interdependent; and constantly fixing, utilizing, and dissipating energy.

Biotic index the diversity of species in an ecosystem is often a good indicator of the presence of pollution. The greater the diversity, the lower the degree of pollution. The biotic index is a systematic survey of invertebrate aquatic organisms used to correlate with river quality.

Climax community the terminal stage of ecological succession in an area.

Competition is a critical factor for organisms in any community. Animals and plants must compete successfully in the community to stay alive.

Community in an ecological sense, community includes all the populations occupying a given area.

Decomposition the breakdown of complex material into simpler substances by chemical or biological processes.

Dissolved oxygen (DO) the amount of oxygen dissolved in a stream in an indication of the degree of health of the stream and its ability to support a balanced aquatic ecosystem.

Ecosystem the community and the nonliving environment functioning together as an ecological system.

Emigration the departure of organisms from one place to take up residence in another area.

Eutrophication the natural aging of a lake or landlocked body of water, which results in organic material being produced in abundance due to a ready supply of nutrients accumulated over the years.

Habitat ecologists use this term to refer to the place where an organism lives.

Heterotroph (living organisms) any living organism that obtains energy by consuming organic substances produced by other organisms.

Immigration the movement of organisms into a new area of residence.

Limiting factor a necessary material that is in short supply. Because of the lack of it, an organism cannot reach its full potential.

Niche the role that an organism plays in its natural ecosystem, including its activities, resource use, and interaction with other organisms.

Nonpoint pollution Sources of pollutants in the landscape (e.g., agricultural runoff).

Point source source of pollutants that involves discharge of pollutants from an identifiable point, such as a smokestack or sewage treatment plant.

Pollution an adverse alteration to the environment by a pollutant.

Population a group of organisms of a single species that inhabit a certain region at a particular time.

Runoff after an organic waste has been applied to a soil, the possibility exists that some of this waste may be transmitted by rainfall, snowmelt, or irrigation runoff into surface waters.

Sewage the liquid wastes from a community. Domestic sewage comes from housing. Industrial sewage is normally from mixed industrial and residential sources.

Succession a process that occurs subsequent to disturbance and involves the progressive replacement of biotic communities with others over time.

Symbiosis a compatible association between dissimilar organisms to their mutual advantage.

Trophic level the feeding position occupied by a given organism in a food chain measured by the number of steps removed from the producers.

12.4 LEVELS OF ORGANIZATION

As Odum explains, "the best way to delimit modern ecology is to consider the concept of levels of organization."[3] Levels of organization can be simplified as shown in Figure 12.1. In this relationship, organs form an organism, organisms of a particular species form a population, and populations occupying a particular area form a community. Communities, interacting with nonliving or abiotic factors, separate in a natural unit to create a stable system known as the ecosystem (the major ecological unit); the part of earth in which ecosystem operates in is known as the biosphere. Tomera points out "every community is influenced by a particular set of abiotic factors."[4] Inorganic

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Organs ⇒ Organism ⇒ Population ⇒ Communities ⇒ Ecosystem ⇒ Biosphere

FIGURE 12.1 Levels of organization. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

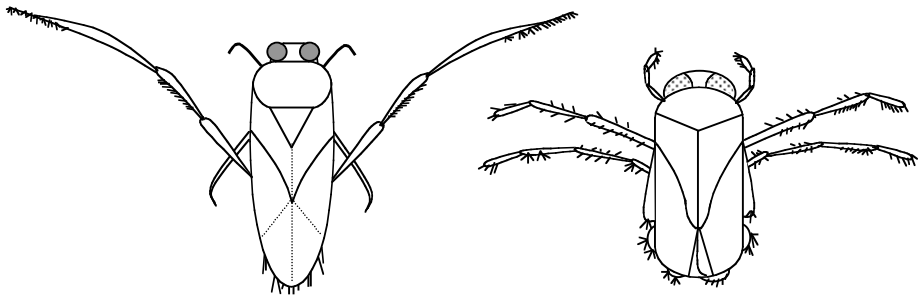

FIGURE 12.2 *Notonecta* (left) and *Corixa* (right) (Adapted from *Basic Ecology,* Odum, E.P., Saunders, Philadelphia, 1983, p. 402. With permission.)

substances such as oxygen, carbon dioxide, several other inorganic substances, and some organic substances represent the abiotic part of the ecosystem.

The physical and biological environment in which an organism lives is referred to as its habitat. For example, the habitat of two common aquatic insects, the backswimmer (*Notonecta*) and the water boatman (*Corixa*) is the littoral zone of ponds and lakes (shallow, vegetation-choked areas) (see Figure 12.2).[5]

Within each level of organization of a particular habitat, each organism has a special role. The role the organism plays in the environment is referred to as its niche. A niche might be that the organism is food for some other organism or is a predator of other organisms. Odum refers to an organism's niche as its "profession".[6] In other words, each organism has a job or role to fulfill in its environment. Although two different species might occupy the same habitat, "niche separation based on food habits" differentiates between two species.[7] Such niche separation can be seen by comparing the niches of the water backswimmer and the water boatman. The backswimmer is an active predator, while the water boatman feeds largely on decaying vegetation.[8]

12.5 ECOSYSTEM

Ecosystem denotes an area that includes all organisms therein and their physical environment. The ecosystem is the major ecological unit in nature. Living organisms and their nonliving environment are inseparably interrelated and interact upon each other to create a self-regulating and self-maintaining system. To create such a system, ecosystems are homeostatic (i.e., they resist any change through natural controls). These natural controls are important in ecology. This is especially the case because it is people through their complex activities who tend to disrupt natural controls.

As stated earlier, the ecosystem encompasses both the living and nonliving factors in a particular environment. The living or biotic part of the ecosystem is formed by two components: autotrophic and heterotrophic. The autotrophic (self-nourishing) component does not require food from its environment, but can manufacture food from inorganic substances. For example, some autotrophic components (plants) manufacture needed energy through photosynthesis. Heterotrophic components, on the other hand, depend upon autotrophic components for food.

The nonliving or abiotic part of the ecosystem is formed by three components: inorganic substances, organic compounds (link biotic and abiotic parts), and climate regime. Figure 12.3 is a simplified diagram showing a few of the living and nonliving components of an ecosystem found in a freshwater pond.

An ecosystem is a cyclic mechanism in which biotic and abiotic materials are constantly exchanged through biogeochemical cycles. Biogeochemical cycles are defined as follows: bio refers to living organisms and geo refers to water, air, rocks or solids. Chemical is concerned with the chemical composition of the earth. Biogeochemical cycles are driven by energy, directly or indirectly from the sun.

Figure 12.3 depicts a pond ecosystem where biotic and abiotic materials are constantly exchanged. Producers construct organic substances through photosynthesis and chemosynthesis. Consumers and decomposers use organic matter as their food and convert it into abiotic components; they dissipate energy fixed by producers through food chains. The abiotic part of the pond in Figure 12.3 is formed of dissolved inorganic and organic compounds and in sediments such as carbon, oxygen, nitrogen, sulfur, calcium, hydrogen, and humic acids. Producers such as rooted plants and phytoplanktons represent the biotic part. Fish, crustaceans, and insect larvae make up the consumers. Mayfly nymphs represent Detrivores, which feed on

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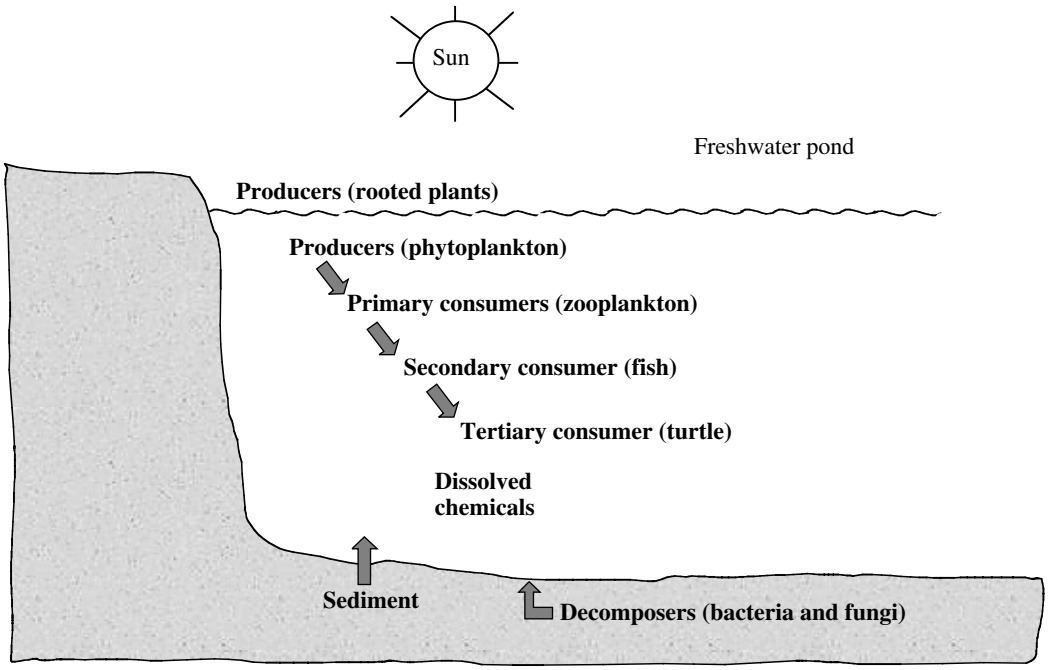

FIGURE 12.3 Major components of a freshwater pond ecosystem. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

organic detritus. Decomposers make up the final biotic part. They include aquatic bacteria and fungi, which are distributed throughout the pond.

As stated earlier, an ecosystem is a cyclic mechanism. From a functional viewpoint, an ecosystem can be analyzed in terms of several factors. The factors important in this study include the biogeochemical cycles (discussed earlier in Chapter 11) and energy and food chains.

12.6 ENERGY FLOW IN THE ECOSYSTEM

Simply defined, energy is the ability or capacity to do work. For an ecosystem to exist, it must have energy. All activities of living organisms involve work, which is the expenditure of energy. This means the degradation of a higher state of energy to a lower state. Two laws govern the flow of energy through an ecosystem: the first and second laws of thermodynamics.

The first law, sometimes called the conservation law, states that energy may not be created or destroyed. The second law states that no energy transformation is 100% efficient, meaning in every energy transformation, some energy is dissipated as heat. The term entropy is used as a measure of the nonavailability of energy to a system. Entropy increases with an increase in dissipation. Because of entropy, input of energy in any system is higher than the output or work done; thus, the resultant, efficiency, is less than 100%.

The interaction of energy and materials in the ecosystem is important. As mentioned in Chapter 11, we discussed biogeochemical nutrient cycles. It is important to remember that it is the flow of energy that drives these cycles. It should also be noted that energy does not cycle as nutrients do in biogeochemical cycles. For example, when food passes from one organism to another, energy contained in the food is reduced systematically until all the energy in the system is dissipated as heat. Price refers to this process as "a unidirectional flow of energy through the system, with no possibility for recycling of energy."[9] When water or nutrients are recycled, energy is required. The energy expended in this recycling is not recyclable.

As mentioned, the principal source of energy for any ecosystem is sunlight. Green plants, through the process of photosynthesis, transform the sun's energy into carbohydrates, which are consumed by animals. This transfer of energy, again, is unidirectional — from producers to consumers. Often this transfer of energy to different organisms is called a food chain. Figure 12.4 shows a simple aquatic food chain.

FIGURE 12.4 Aquatic food chain. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

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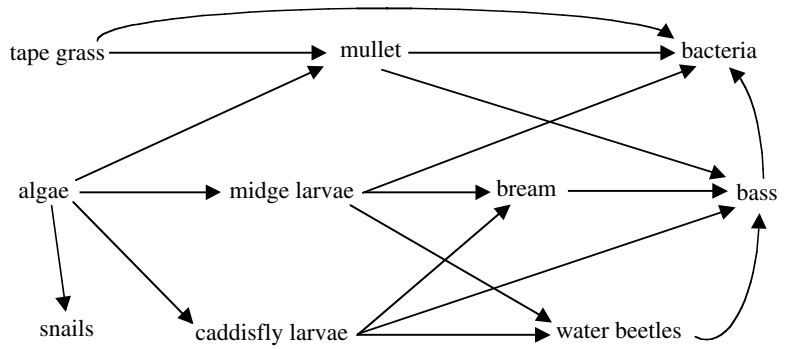

FIGURE 12.5 Aquatic food web. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

All organisms, alive or dead, are potential sources of food for other organisms. All organisms that share the same general type of food in a food chain are said to be at the same trophic level (nourishment or feeding level). Since green plants use sunlight to produce food for animals, they are called the producers, or the first trophic level. The herbivores, which eat plants directly, are called the second trophic level or the primary consumers. The carnivores are flesh-eating consumers; they include several trophic levels from the third on up. At each transfer, a large amount of energy (about 80 to 90%) is lost as heat and wastes. Thus, nature normally limits food chains to four or five links. In aquatic ecosystems, food chains are commonly longer than those on land. The aquatic food chain is longer because several predatory fish may be feeding on the plant consumers. Even so, the built-in inefficiency of the energy transfer process prevents development of extremely long food chains.

Only a few simple food chains are found in nature. Most simple food chains are interlocked. This interlocking of food chains forms a food web. Most ecosystems support a complex food web. A food web involves animals that do not feed on one trophic level. For example, humans feed on both plants and animals. An organism in a food web may occupy one or more trophic levels. Trophic level is determined by an organism's role in its particular community, not by its species. Food chains and webs help to explain how energy moves through an ecosystem.

An important trophic level of the food web is comprised of the decomposers. The decomposers feed on dead plants or animals and play an important role in recycling nutrients in the ecosystem. Simply, there is no waste in ecosystems. All organisms, dead or alive, are potential sources of food for other organisms. An example of an aquatic food web is shown in Figure 12.5.

12.7 FOOD CHAIN EFFICIENCY

Earlier, we pointed out that energy from the sun is captured (via photosynthesis) by green plants and used to make food. Most of this energy is used to carry on the plant's life activities. The rest of the energy is passed on as food to the next level of the food chain.

Nature limits the amount of energy that is accessible to organisms within each food chain. Not all food energy is transferred from one trophic level to the next. Only about 10% (10% rule) of the amount of energy is actually transferred through a food chain. For example, if we apply the 10% rule to the diatoms-copepods-minnows-medium fish-large fish food chain shown in Figure 12.6, we can predict that 1000 g of diatoms produce 100 g of copepods, which will produce 10 g of minnows, which will produce 1 g of medium fish, which, in turn, will produce 0.1 g of large fish. Only about 10% of the chemical energy available at each trophic level is transferred and stored in usable form at the next level. The other 90% is lost to the environment as low-quality heat in accordance with the second law of thermodynamics.

12.8 ECOLOGICAL PYRAMIDS

In the food chain, from the producer to the final consumer, it is clear that a particular community in nature often consists of several small organisms associated with a smaller and smaller number of larger organisms. A grassy field, for example, has a larger number of grasses and other small plants, a smaller number of herbivores like rabbits, and an even smaller number of carnivores like fox. The practical significance of this is that we must have several more producers than consumers.

This pound-for-pound relationship, where it takes more producers than consumers, can be demonstrated graphically by building an ecological pyramid. In an ecological pyramid, separate levels represent the number of organisms at various trophic levels in a food chain or bars placed one above the other with a base formed by producers and the apex formed by the final consumer. The pyramid shape is formed due to a great amount of energy loss at each trophic level. The same is true if the corresponding biomass or energy substitutes numbers. Ecologists generally use three types of ecological pyramids: pyramids of

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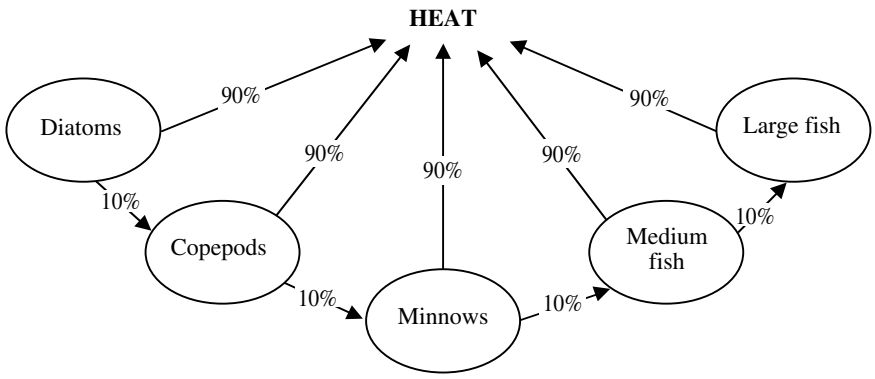

FIGURE 12.6 Simple food chain. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

number, biomass, and energy. Obviously, there will be differences among them. Some generalizations:

1. Energy pyramids must always be larger at the base than at the top (because of the second law of thermodynamics some energy is always wasted).
2. Biomass pyramids (in which biomass is used as an indicator of production) are usually pyramid-shaped. This is particularly true of terrestrial systems and aquatic ones dominated by large plants (marshes), in which consumption by heterotroph is low and organic matter accumulates with time. However, biomass pyramids can sometimes be inverted. This is common in aquatic ecosystems, in which the primary producers are microscopic planktonic organisms that multiply very rapidly, have very short life spans, and have heavy grazing by herbivores. At any single point in time, the amount of biomass in primary producers is less than that in larger, long-lived animals that consume primary producers.
3. Numbers pyramids can have various shapes (and not be pyramids at all) depending on the sizes of the organisms that make up the trophic levels. In forests, the primary producers are large trees and the herbivore level usually consists of insects, so the base of the pyramid is smaller than the herbivore level above it. In grasslands, the number of primary producers (grasses) is much larger than that of the herbivores above (large grazing animals).[10]

12.9 PRODUCTIVITY

As mentioned, the flow of energy through an ecosystem starts with the fixation of sunlight by plants through photosynthesis. In evaluating an ecosystem, the measurement of photosynthesis is important. Ecosystems may be classified into highly productive or less productive. Therefore, the study of ecosystems must involve some measure of the productivity of that ecosystem.

Primary production is the rate at which the ecosystem's primary producers capture and store a given amount of energy, in a specified time interval. In simpler terms, primary productivity is a measure of the rate at which photosynthesis occurs. Four successive steps in the production process are:

1. Gross primary productivity — The total rate of photosynthesis in an ecosystem during a specified interval.
2. Net primary productivity — The rate of energy storage in plant tissues in excess of the rate of aerobic respiration by primary producers.
3. Net community productivity — The rate of storage of organic matter not used.
4. Secondary productivity — The rate of energy storage at consumer levels.

When attempting to comprehend the significance of the term productivity as it relates to ecosystems, it is wise to consider an example. Consider the productivity of an agricultural ecosystem such as a wheat field. Often its productivity is expressed as the number of bushels produced per acre. This is an example of the harvest method for measuring productivity. For a natural ecosystem, several 1 m^2-plots are marked off, and the entire area is harvested and weighed to give an estimate of productivity as grams of biomass per square meter per given time interval. From this method, a measure of net primary production (net yield) can be measured.

Productivity, both in the natural and cultured ecosystem, may not only vary considerably between types of ecosystems, but also within the same ecosystem. Several factors influence year-to-year productivity within an ecosystem. Such factors as temperature, availability of nutrients, fire, animal grazing, and human cultivation activities are

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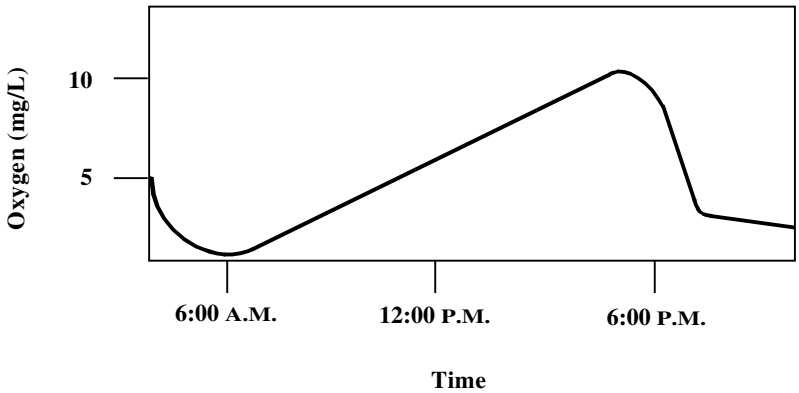

FIGURE 12.7 The diurnal oxygen curve for an aquatic ecosystem. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

directly or indirectly related to the productivity of a particular ecosystem.

Productivity can be measured in several different ways in the aquatic ecosystem. For example, the production of oxygen may be used to determine productivity. Oxygen content may be measured in several ways. One way is to measure it in the water every few hours for a period of 24 hours. During daylight, when photosynthesis is occurring, the oxygen concentration should rise. At night the oxygen level should drop. The oxygen level can be measured by using a simple *x*-*y* graph. The oxygen level can be plotted on the *y*-axis with time plotted on the *x*-axis, as shown in Figure 12.7.

Another method of measuring oxygen production in aquatic ecosystems is to use light and dark bottles. Biochemical oxygen demand (BOD) bottles (300 mL) are filled with water to a particular height. One of the bottles is tested for the initial dissolved oxygen (DO); the other two bottles (one clear, one dark) are suspended in the water at the depth they were taken from. After a 12-h period, the bottles are collected and the DO values for each bottle are recorded. Once the oxygen production is known, the productivity in terms of grams per meters per day can be calculated.

In the aquatic ecosystem, pollution can have a profound impact upon the system's productivity.

12.10 POPULATION ECOLOGY

Webster's Third New International Dictionary defines population as "the total number or amount of things especially within a given area; the organisms inhabiting a particular area or biotype; and a group of interbreeding biotypes that represents the level of organization at which speciation begins."

The term population is interpreted differently in various sciences. For example, in human demography a population is a set of humans in a given area. In genetics, a population is a group of interbreeding individuals of the same species that is isolated from other groups. In population ecology, a population is a group of individuals of the same species inhabiting the same area.

If we wanted to study the organisms in a slow moving stream or stream pond, we would have two options. We could study each fish, aquatic plant, crustacean, and insect one by one. In that case, we would be studying individuals. It would be easier to do this if the subject were trout, but it would be difficult to separate and study each aquatic plant.

The second option would be to study all of the trout, all of the insects of each specific kind, and all of a certain aquatic plant type in the stream or pond at the time of the study. When ecologists study a group of the same kind of individuals in a given location at a given time, they are investigating a *population*. When attempting to determine the population of a particular species, it is important to remember that time is a factor. Whether it is at various times during the day, during the different seasons, or from year to year, time is important because populations change.

Population density may change dramatically. For example, if a dam is closed off in a river midway through spawning season, with no provision allowed for fish movement upstream (a fish ladder), it would drastically decrease the density of spawning salmon upstream. In fact, river dams are recognized as one of the proximal causes of the salmon's decline, but the specific cause-and-effect relationship cannot be easily determined. The specific effects (i.e., the number of fish eliminated from the population) of damming rivers leading to salmon spawning grounds is difficult to measure.[11]

Along with the swift and sometimes unpredictable consequences of change, it can be difficult to draw exact boundaries between various populations. The population density or level of a species depends on natality, mortality, immigration, and emigration. Changes in population density are the result of both births and deaths. The birth rate of a population is called natality and the death rate is called

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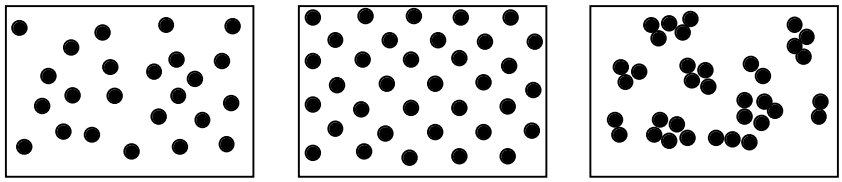

FIGURE 12.8 Basic patterns of distribution (Adapted from Odum E.P., *Fundamentals of Ecology,* Saunders, Philadelphia, 1971, p. 205. With permission.)

mortality. In aquatic populations, two factors besides natality and mortality can affect density. For example, in a run of returning salmon to their spawning grounds, the density could vary as more salmon migrated in or as others left the run for their own spawning grounds. The arrival of new salmon to a population from other places is termed immigration (ingress). The departure of salmon from a population is called emigration (egress). Natality and immigration increase population density, whereas mortality and emigration decrease it. The net increase in population is the difference between these two sets of factors.

Each organism occupies only those areas that can provide for its requirements, resulting in an irregular distribution. How a particular population is distributed within a given area has considerable influence on density. As shown in Figure 12.8, organisms in nature may be distributed in three ways.

In a random distribution, there is an equal probability of an organism occupying any point in space, and "each individual is independent of the others."[12]

In a regular or uniform distribution, organisms are spaced more evenly; they are not distributed by chance. Animals compete with each other and effectively defend a specific territory, excluding other individuals of the same species. In regular or uniform distribution, the competition between individuals can be quite severe and antagonistic to the point where spacing generated is quite even.

The most common distribution is the contagious or clumped distribution where organisms are found in groups; this may reflect the heterogeneity of the habitat.

Organisms that exhibit a contagious or clumped distribution may develop social hierarchies in order to live together more effectively. Animals within the same species have evolved many symbolic aggressive displays that carry meanings that are not only mutually understood, but also prevent injury or death within the same species.

The size of animal populations is constantly changing due to natality, mortality, emigration, and immigration. As mentioned, the population size will increase if the natality and immigration rates are high. On the other hand, it will decrease if the mortality and emigration rates are high. Each population has an upper limit on size, often called the carrying capacity. Carrying capacity is the optimum number of species' individuals that can survive in a specific area over time. Stated differently, the carrying capacity is the maximum number of species that can be supported in a bioregion. A pond may be able to support only a dozen frogs depending on the food resources for the frogs in the pond. If there were 30 frogs in the same pond, at least half of them would probably die because the pond environment would not have enough food for them to live. Carrying capacity is based on the quantity of food supplies, the physical space available, the degree of predation, and several other environmental factors.

The carrying capacity is of two types: ultimate and environmental. Ultimate carrying capacity is the theoretical maximum density — the maximum number of individuals of a species in a place that can support itself without rendering the place uninhabitable. The environmental carrying capacity is the actual maximum population density that a species maintains in an area. Ultimate carrying capacity is always higher than environmental. Ecologists have concluded that a major factor that affects population stability or persistence is species diversity. Species diversity is a measure of the number of species and their relative abundance.

If the stress on an ecosystem is small, the ecosystem can usually adapt quite easily. Moreover, even when severe stress occurs, ecosystems have a way of adapting. Severe environmental change to an ecosystem can result from such natural occurrences as fires, earthquakes, and floods and from people-induced changes such as land clearing, surface mining, and pollution. One of the most important applications of species diversity is in the evaluation of pollution. Stress of any kind will reduce the species diversity of an ecosystem to a significant degree. In the case of domestic sewage pollution, for example, the stress is caused by a lack of DO for aquatic organisms.

Ecosystems can and do change. For example, if a fire devastates a forest, it will eventually grow back because of ecological succession. Ecological succession is the observed process of change (a normal occurrence in nature) in the species structure of an ecological community over time. Succession usually occurs in an orderly, predictable manner. It involves the entire system. The science of ecology has developed to such a point that ecologists are now able to predict several years in advance what will occur in a given ecosystem. For example, scientists know that if a burned-out forest region receives light, water, nutrients,

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and an influx or immigration of animals and seeds, it will eventually develop into another forest through a sequence of steps or stages. Ecologists recognize two types of ecological succession: primary and secondary. The particular type that takes place depends on the condition at a particular site at the beginning of the process.

Primary succession, sometimes called bare-rock succession, occurs on surfaces, such as hardened volcanic lava, bare rock, and sand dunes, where no soil exists and where nothing has ever grown before (See Figure 12.9). In order to grow, plants need soil. Soil must form on the bare rock before succession can begin. Usually this soil formation process results from weathering. Atmospheric exposure — weathering, wind, rain, and frost — forms tiny cracks and holes in rock surfaces. Water collects in the rock fissures and slowly dissolves the minerals out of the rock's surface. A pioneer soil layer is formed from the dissolved minerals and supports such plants as lichens. Lichens gradually cover the rock surface and secrete carbonic acid that dissolves additional minerals from the rock. Eventually, mosses replace the lichens. Organisms called decomposers move in and feed on dead lichen and moss. A few small animals, such as mites and spiders, arrive next. The result is what is known as a pioneer community. The pioneer community is defined as the first successful integration of plants, animals, and decomposers into a bare-rock community.

After several years, the pioneer community builds up enough organic matter in its soil to be able to support rooted plants like herbs and shrubs. Eventually, the pioneer community is crowded out and is replaced by a different environment. This works to thicken the upper soil layers. The progression continues through several other stages until a mature or climax ecosystem is developed several decades later. In bare-rock succession, each stage in the complex succession pattern dooms the stage that existed before it. Secondary succession is the most common type of succession. Secondary succession occurs in an area where the natural vegetation has been removed or destroyed but the soil is not destroyed. For example, succession that occurs in abandoned farm fields, known as old-field succession, illustrates secondary succession. An example of secondary succession can be seen in the Piedmont region of North Carolina. Early settlers of the area cleared away the native oak-hickory forests and cultivated the land. In the ensuing years, the soil became depleted of nutrients, reducing the soil's fertility. As a result, farming ceased in the region a few generations later, and the fields were abandoned. Some 150 to 200 years after abandonment, the climax oak-hickory forest was restored.

In a stream ecosystem, growth is enhanced by biotic and abiotic factors. These factors include:

1. Ability to produce offspring
2. Ability to adapt to new environments

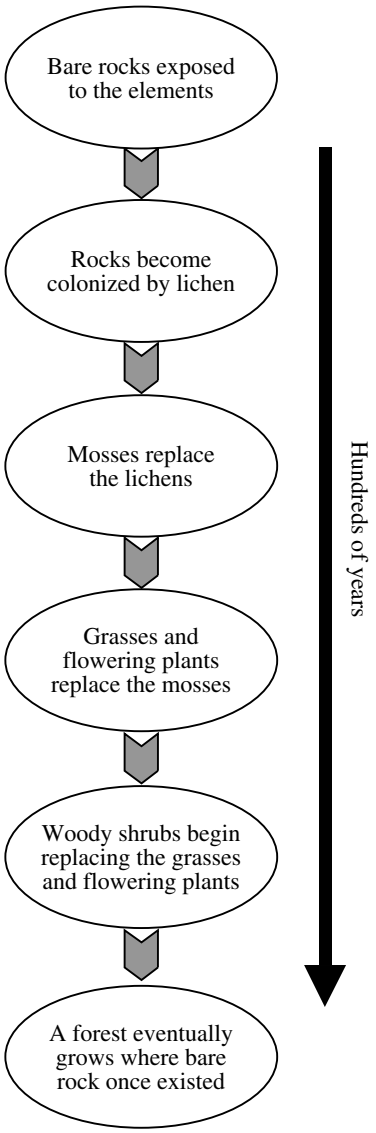

FIGURE 12.9 Bare-rock succession (Adapted from Tomera, A.N., *Understanding Basic Ecological Concepts,* J. Weston Walch Publ., Portland, ME, 1989, p. 67. With permission.)

3. Ability to migrate to new territories
4. Ability to compete with species for food and space to live
5. Ability to blend into the environment so as not to be eaten
6. Ability to find food
7. Ability to defend itself from enemies
8. Favorable light
9. Favorable temperature
10. Favorable DO content
11. Sufficient water level

The biotic and abiotic factors in an aquatic ecosystem that reduce growth include:

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1. Predators
2. Disease
3. Parasites
4. Pollution
5. Competition for space and food
6. Unfavorable stream conditions (i.e., low water levels)
7. Lack of food

In regards to stability in a freshwater ecosystem, the higher the species diversity the greater the inertia and resilience of the ecosystem. At the same time, when the species diversity is high within a stream ecosystem, a population within the stream can be out of control because of an imbalance between growth and reduction factors, with the ecosystem at the same time still remaining stable. In regards to instability in a freshwater ecosystem, recall that imbalance occurs when growth and reduction factors are out of balance. For example, when sewage is accidentally dumped into a stream, the stream ecosystem, via the self-purification process (discussed later) responds and returns to normal. This process is described as follows:

1. Raw sewage is dumped into the stream.
2. Decreases the oxygen available as the detritus food chain breaks down the sewage.
3. Some fish die at the pollution site and down stream.
4. Sewage is broken down and washes out to sea and is finally broken down in the ocean.
5. Oxygen levels return to normal.
6. Fish populations that were deleted are restored as fish about the spill reproduce and the young occupy the real estate formerly occupied by the dead fish.
7. Populations all return to normal.

A shift in balance in a stream's ecosystem (or in any ecosystem) similar to the one just described is a common occurrence. In this particular case, the stream responded (on its own) to the imbalance the sewage caused and through the self-purification process returned to normal. Recall that succession is the method by which an ecosystem either forms itself or heals itself. We can say that a type of succession has occurred in the polluted stream described above because in the end it healed itself. More importantly, this healing process is a good thing; otherwise, long ago there would have been few streams on Earth suitable for much more than the dumping of garbage.

In summary, through research and observation, ecologists have found that the succession patterns in different ecosystems usually display common characteristics. First, succession brings about changes in the plant and animal members present. Second, organic matter increases from stage to stage. Finally, as each stage progresses, there is a tendency toward greater stability or persistence. Remember, succession is usually predictable. This is the case unless humans interfere.

12.11 STREAM GENESIS AND STRUCTURE

Consider the following:

> Early in the spring on a snow and ice-covered high alpine meadow, the time and place the water cycle continues. The cycle's main component, water, has been held in reserve — literally frozen — for the long dark winter months, but with longer, warmer spring days, the sun is higher, more direct, and of longer duration, and the frozen masses of water respond to the increased warmth. The melt begins with a single drop, then two, then increasingly. As the snow and ice melts, the drops join a chorus that continues unending; they fall from their ice-bound lip to the bare rock and soil terrain below.
>
> The terrain the snow-melt strikes is not like glacial till, the unconsolidated, heterogeneous mixture of clay, sand, gravel, and boulders, dug-out, ground-out, and exposed by the force of a huge, slow, and inexorably moving glacier. Instead, this soil and rock ground is exposed to the falling drops of snow-melt because of a combination of wind and tiny, enduring force exerted by drops of water as over seasons after season they collide with the thin soil cover, exposing the intimate bones of the earth.
>
> Gradually, the single drops increase to a small rush — they join to form a splashing, rebounding, helter-skelter cascade; many separate rivulets that trickle, then run their way down the face of the granite mountain. At an indented ledge halfway down the mountain slope, a pool forms whose beauty, clarity, and sweet iciness provides the visitor with an incomprehensible, incomparable gift — a blessing from earth.
>
> The mountain pool fills slowly, tranquil under the blue sky, reflecting the pines, snow, and sky around and above it. It is an open invitation to lie down and drink, and to peer into the glass-clear, deep phantom blue-green eye that is so clear that it seems possible to reach down over 50 ft and touch the very bowels of the mountain. The pool has no transition from shallow margin to depth; it is simply deep and pure. As the pool fills with more melt water, we wish to freeze time, to hold this place and this pool in its perfect state forever; it is such a rarity to us in our modern world. However, this cannot be — Mother Nature calls, prodding, urging — and for a brief instant, the water laps in the breeze against the outermost edge of the ridge, and then a trickle flows over the rim. The giant hand of gravity reaches out and tips the overflowing melt onward and it continues the downward journey, following the path of least resistance to its next destination, several thousand feet below.

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The overflow, still high in altitude with its rock-strewn bed bent downward toward the sea, meets the angled, broken rocks below. It bounces, bursts, and mists its way against steep, V-shaped walls that form a small valley carved out over time by water and the forces of the earth.

Within the valley confines, the melt water has grown from drops to rivulets to a small mass of flowing water. It flows through what is at first a narrow opening, gaining strength, speed, and power as the V-shaped valley widens to form a U-shape. The journey continues as the water mass picks up speed and tumbles over massive boulders, and then slows again.

At a larger but shallower pool, waters from higher elevations have joined the main body — from the hillsides, crevices, springs, rills, and mountain creeks. At the influent poolsides, all appears peaceful, quiet, and restful, but not far away, at the effluent end of the pool, gravity takes control again. The overflow is flung over the jagged lip; it cascades downward several hundred feet, where the waterfall again brings its load to a violent, mist-filled meeting.

The water separates and joins repeatedly, forming a deep, furious, wild stream that calms gradually as it continues to flow over lands that are less steep. The waters widen into pools overhung by vegetation, surrounded by tall trees. The pure, crystalline waters have become progressively discolored on their downward journey, stained brown-black with humic acid, and literally filled with suspended sediments; the once-pure stream is now muddy.

The mass divides and flows in different directions, over different landscapes. Small streams divert and flow into open country. Different soils work to retain or speed the waters, and in some places, the waters spread out into shallow swamps, bogs, marshes, fens, or mires. Other streams pause long enough to fill deep depressions in the land and form lakes. For a time, the water remains and pauses in its journey to the sea. This is only a short-term pause because lakes are only a short-term resting place in the water cycle. The water will eventually move on, by evaporation or seepage, into groundwater. Other portions of the water mass stay with the main flow, and the speed of flow changes to form a river that braids its way through the landscape, heading for the sea. As it changes speed and slows, the river bottom changes from rock and stone to silt and clay. Plants begin to grow, stems thicken, and leaves broaden. The river is now full of life and the nutrients needed to sustain life. The river courses onward; its destiny is met when the flowing rich mass slows its last and finally spills into the sea.

Freshwater systems are divided into two broad categories: running waters (lotic systems) and standing waters (lentic systems). We concentrate on lotic systems, although many of the principles described herein apply to other freshwater surface bodies as well, which are known by common names. Some examples include seeps, springs, brooks, branches, creeks, streams, and rivers. Again, because it is the best term to use in freshwater ecology, it is the stream we are concerned with here. Although there is no standard scientific definition of a stream, it is usually distinguished subjectively as follows: a stream is of intermediate size that can be waded from one side to the other.

Physical processes involved in the formation of a stream are important to the ecology of the stream. This is because stream channel and flow characteristics directly influence the functioning of the stream's ecosystem, and the biota found therein. In this section, we discuss the pathways of water flow contributing to stream flow; namely, we discuss precipitation inputs as they contribute to flow. We also discuss stream flow discharge, transport of material, characteristics of stream channels, stream profile, sinuosity, the floodplain, pool-riffle sequences, and depositional features; all directly or indirectly impact the ecology of the stream.

12.11.1 Water Flow in a Stream

Most elementary students learn early in their education process that water on Earth flows downhill — from land to the sea. They may or may not be told that water flows downhill toward the sea by various routes.

At this time, the route (or pathway) that we are primarily concerned with is the surface water route taken by surface water runoff. Surface runoff is dependent on various factors. For example, climate, vegetation, topography, geology, soil characteristics, and land-use determine how much surface runoff occurs compared with other pathways.

The primary source (input) of water to total surface runoff is precipitation. This is the case even though a substantial portion of all precipitation input returns directly to the atmosphere by evapotranspiration. As the name suggests, evapotranspiration is a combination process whereby water in plant tissue and in the soil evaporates and transpires to water vapor in the atmosphere.

Probably the easiest way to understand precipitation's input to surface water runoff is to take a closer look at this precipitation input. We stated that a substantial portion of precipitation input returns directly to the atmosphere by evapotranspiration. It is also important to point out that when precipitation occurs, some rainwater is intercepted by vegetation where it evaporates, never reaching the ground or being absorbed by plants.

A large portion of the rainwater that reaches the surface on ground, in lakes, and streams also evaporates directly back to the atmosphere.

Although plants display a special adaptation to minimize transpiration, plants still lose water to the atmosphere during the exchange of gases necessary for photosynthesis.

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Notwithstanding the large percentage of precipitation that evaporates, rain- or melt-water that reaches the ground surface follows several pathways in reaching a stream channel or groundwater.

Soil can absorb rainfall to its infiltration capacity (i.e., to its maximum rate). During a rain event, this capacity decreases. Any rainfall in excess of infiltration capacity accumulates on the surface. When this surface water exceeds the depression storage capacity of the surface, it moves as an irregular sheet of overland flow. In arid areas, overland flow is likely because of the low permeability of the soil. Overland flow is also likely when the surface is frozen or when human activities have rendered the land surface less permeable. In humid areas, where infiltration capacities are high, overland flow is rare.

In rain events where the infiltration capacity of the soil is not exceeded, rain penetrates the soil and eventually reaches the groundwater where it discharges to the stream slowly and over a long period. This phenomenon helps to explain why stream flow through a dry weather region remains constant; the flow is continuously augmented by groundwater. This type of stream is known as a perennial stream, as opposed to an intermittent one, because the flow continues during periods of no rainfall.

When a stream courses through a humid region, it is fed water via the water table, which slopes toward the stream channel. Discharge from the water table into the stream accounts for flow during periods without precipitation; this explains why this flow increases, even without tributary input, as one proceeds downstream. Such streams are called gaining or effluent, opposed to losing or influent streams that lose water into the ground (see Figure 12.10). The same stream can shift between gaining and losing conditions along its course because of changes in underlying strata and local climate.

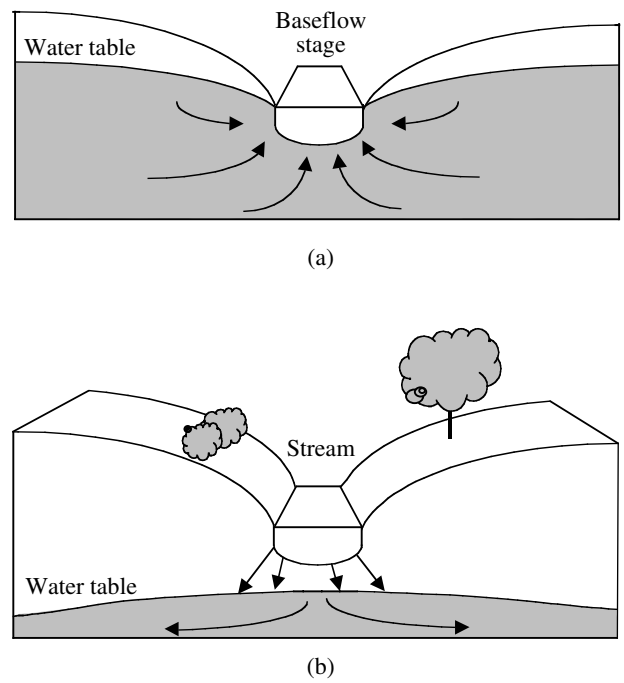

FIGURE 12.10 (a) Cross-section of a gaining stream; (b) cross-section of a losing stream. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

12.11.2 Stream Water Discharge

The current velocity (speed) of water (driven by gravitational energy) in a channel varies considerably within a stream's cross section, owing to friction with the bottom and sides, sediment, and the atmosphere, and to sinuosity (bending or curving) and obstructions. Highest velocities are found where friction is least, generally at or near the surface and near the center of the channel. In deeper streams, current velocity is greatest just below the surface due to the friction with the atmosphere; in shallower streams, current velocity is greatest at the surface due to friction with the bed. Velocity decreases as a function of depth, approaching zero at the substrate surface.

12.11.3 Transport of Material

Water flowing in a channel may exhibit laminar flow (parallel layers of water shear over one another vertically) or turbulent flow (complex mixing). In streams, laminar flow is uncommon, except at boundaries where flow is very low and in groundwater. Thus, the flow in streams generally is turbulent. Turbulence exerts a shearing force that causes particles to move along the streambed by pushing, rolling, and skipping; this referred to as bed load. This same shear causes turbulent eddies that entrain particles in suspension (called the suspended load — particles size under 0.06 mm).

Entrainment is the incorporation of particles when stream velocity exceeds the entraining velocity for a particular particle size. The entrained particles in suspension (suspended load) also include fine sediment, primarily clays, silts and fine sands that require only low velocities and minor turbulence to remain in suspension. These are referred to as wash load (under 0.002 mm). The suspended load includes the wash load and coarser materials (at lower flows). Together the suspended load and bed load constitutes the solid load. It is important to note that in bedrock streams the bed load will be a lower fraction than in alluvial streams where channels are composed of easily transported material.

A substantial amount of material is also transported as the dissolved load. Solutes are generally derived from chemical weathering of bedrock and soils, and their contribution is greatest in subsurface flows and in regions of limestone geology.

The relative amount of material transported as solute rather than solid load depends on basin characteristics: lithology (i.e., the physical character of rock) and hydrologic pathways. In areas of very high runoff, the contribution of

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solutes approaches or exceeds sediment load, whereas in dry regions, sediments make up as much as 90% of the total load.

Deposition occurs when stream competence (i.e., the largest particle that can be moved as bedload, and the critical erosion — competent — velocity is the lowest velocity at which a particle resting on the streambed will move) falls below a given velocity. Simply stated, the size of the particle that can be eroded and transported is a function of current velocity.

Sand particles are the most easily eroded. The greater the mass of larger particles (e.g., coarse gravel), the higher the initial current velocities must be for movement. Smaller particles (silts and clays) require even greater initial velocities because they are cohesive and present smaller, streamlined surfaces to the flow. Once in transport, particles will continue in motion at somewhat slower velocities than initially required to initiate movement and will settle at still lower velocities.

Particle movement is determined by size, flow conditions, and mode of entrainment. Particles over 0.02 mm (medium-coarse sand size) tend to move by rolling or sliding along the channel bed as traction load. When sand particles fall out of the flow, they move by saltation or repeated bouncing. Particles under 0.06 mm (silt) move as suspended load, and particles under 0.002 mm (clay), move as wash load. Unless the supply of sediments becomes depleted the concentration and amount of transported solids increases. Discharge is usually too low throughout most of the year to scrape or scour, shape channels, or move significant quantities of sediment in all but sand-bed streams, which can experience change more rapidly. During extreme events, the greatest scour occurs and the amount of material removed increases dramatically.

Sediment inflow into streams can both be increased and decreased because of human activities. For example, poor agricultural practices and deforestation greatly increase erosion. On the other hand, fabricated structures such as dams and channel diversions, can greatly reduce sediment inflow.

12.11.4 Characteristics of Stream Channels

Flowing waters (rivers and streams) determine their own channels, and these channels exhibit relationships attesting to the operation of physical laws — laws that are not yet fully understood. The development of stream channels and entire drainage networks, and the existence of various regular patterns in the shape of channels, indicate that streams are in a state of dynamic equilibrium between erosion (sediment loading) and deposition (sediment deposit); they are also governed by common hydraulic processes. Because channel geometry is four-dimensional with a long profile, cross section, depth, and slope profile, and because these mutually adjust over a time scale as short as years and as long as centuries or more, cause and effect relationships are difficult to establish. Other variables that are presumed to interact as the stream achieves its graded state include width and depth, velocity, size of sediment load, bed roughness, and the degree of braiding (sinuosity).

12.11.5 Stream Profiles

Mainly because of gravity, most streams exhibit a downstream decrease in gradient along their length. Beginning at the headwaters, the steep gradient becomes less steep as one proceeds downstream, resulting in a concave longitudinal profile. Though diverse geography provides for almost unlimited variation, a lengthy stream that originates in a mountainous area typically comes into existence as a series of springs and rivulets; these coalesce into a fast-flowing, turbulent mountain stream, and the addition of tributaries results in a large and smoothly flowing river that winds through the lowlands to the sea.

When studying a stream system of any length, it becomes readily apparent (almost from the start) that what we are studying is a body of flowing water that varies considerably from place to place along its length. For example, a common variable — the results of which can be readily seen — is whenever discharge increases, causing corresponding changes in the stream's width, depth, and velocity. In addition to physical changes that occur from location to location along a stream's course, there is a legion of biological variables that correlate with stream size and distance downstream. The most apparent and striking changes are in steepness of slope and in the transition from a shallow stream with large boulders and a stony substrate to a deep stream with a sandy substrate.

The particle size of bed material at various locations is also variable along the stream's course. The particle size usually shifts from an abundance of coarser material upstream to mainly finer material in downstream areas.

12.11.6 Sinuosity

Unless forced by man in the form of heavily regulated and channelized streams, straight channels are uncommon. Stream flow creates distinctive landforms composed of straight (usually in appearance only), meandering, and braided channels; channel networks; and floodplains. Simply put: flowing water will follow a sinuous course. The most commonly used measure is the sinuosity index (SI). Sinuosity equals 1 in straight channels and more than 1 in sinuous channels.

Meandering is the natural tendency for alluvial channels and is usually defined as an arbitrarily extreme level of sinuosity, typically a SI greater than 1.5. Many variables affect the degree of sinuosity.

Even in many natural channel sections of a stream course that appear straight, meandering occurs in the line of maximum water or channel depth (known as the thalweg).

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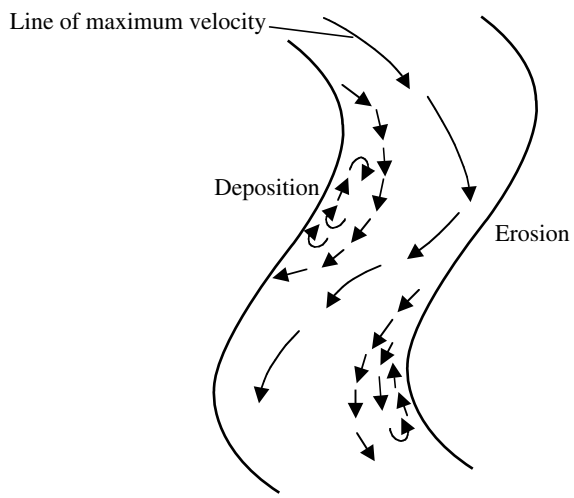

FIGURE 12.11 A meandering reach. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

Keep in mind that a stream has to meander, that is how they renew themselves. By meandering, they wash plants and soil from the land into their waters, and these serve as nutrients for the plants in the rivers. If rivers are not allowed to meander, if they are channelized — the amount of life they can support will gradually decrease. Ultimately that means less fish and less bald eagles, herons, and other fishing birds.[13]

Meander flow follows predictable pattern and causes regular regions of erosion and deposition (see Figure 12.11). The streamlines of maximum velocity and the deepest part of the channel lie close to the outer side of each bend and cross over near the point of inflection between the banks (see Figure 12.11). A huge elevation of water at the outside of a bend causes a helical flow of water toward the opposite bank. In addition, a separation of surface flow causes a back eddy. The result is zones of erosion and deposition, and explains why point bars develop in a downstream direction in depositional zones.

12.11.7 Bars, Riffles, and Pools

Implicit in the morphology and formation of meanders are bars, riffles, and pools. Bars develop by deposition in slower, less competent flow on either side of the sinuous mainstream. Onward moving water, depleted of bed load, regains competence and shears a pool in the meander, reloading the stream for the next bar. Alternating bars migrate to form riffles (see Figure 12.12).

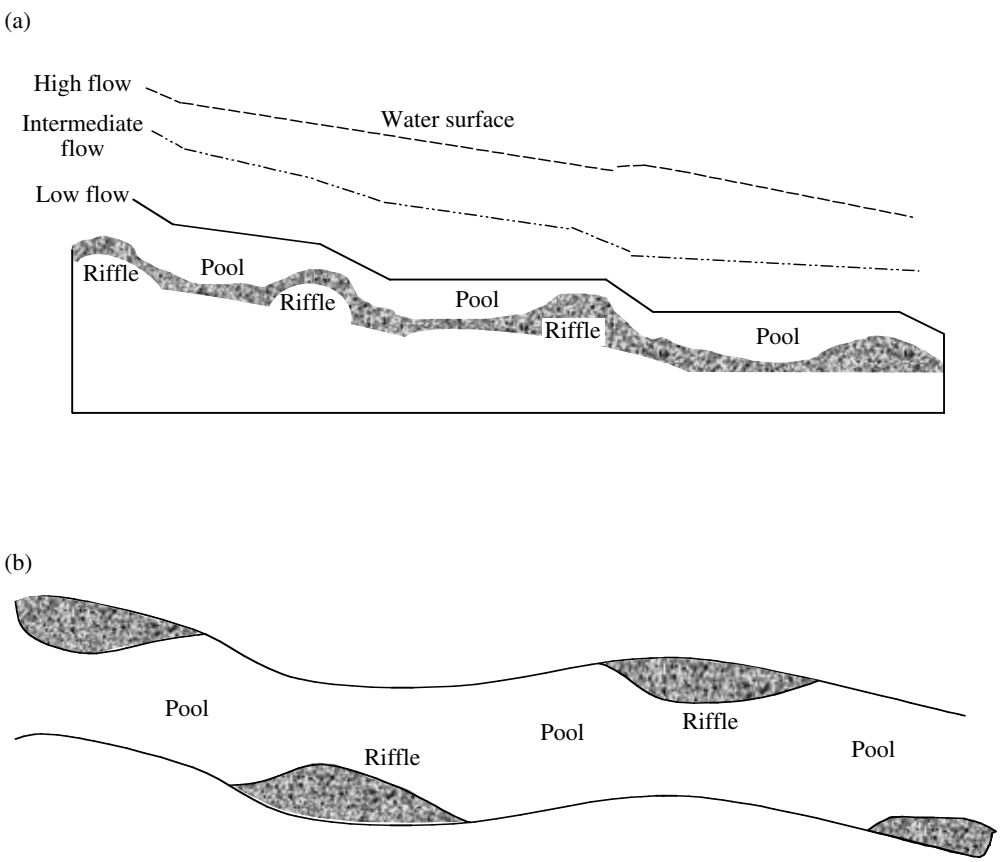

FIGURE 12.12 (a) Longitudinal profile of a riffle-pool sequence; (b) plain view of riffle-pool sequence. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

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As stream flow continues along its course, a pool-riffle sequence is formed. The riffle is a mound or hillock and the pool is a depression.

12.11.8 The Floodplain

A stream channel influences the shape of the valley floor through which it courses. The self-formed, self-adjusted flat area near to the stream is the floodplain, which loosely describes the valley floor prone to periodic inundation during over-bank discharges. What is not commonly known is that valley flooding is a regular and natural behavior of the stream.

A stream's aquatic community has several unique characteristics. The aquatic community operates under the same ecologic principles as terrestrial ecosystems. However, the physical structure of the community is more isolated and exhibits limiting factors that are very different than the limiting factors of a terrestrial ecosystem. Certain materials and conditions are necessary for the growth and reproduction of organisms. If a farmer plants wheat in a field containing too little nitrogen, it will stop growing when it has used up the available nitrogen, even if the wheat's requirements for oxygen, water, potassium, and other nutrients are met. In this particular case, nitrogen is said to be the limiting factor. A limiting factor is a condition or a substance (the resource in shortest supply), which limits the presence and success of an organism or a group of organisms in an area.

Even the smallest mountain stream provides an astonishing number of different places for aquatic organisms to live, or habitats. If it is a rocky stream, every rock of the substrate provides several different habitats. On the side facing upriver, organisms with special adaptations that are very good at clinging to rock do well here. On the side that faces downriver, a certain degree of shelter is provided from current, but still allows organisms to hunt for food. The top of a rock, if it contacts air, is a good place for organisms that cannot breathe underwater and need to surface now and then. Underneath the rock is a popular place for organisms that hide to prevent predation. Normal stream life can be compared to that of a "balanced aquarium."[14] Nature continuously strives to provide clean, healthy, normal streams. This is accomplished by maintaining the stream's flora and fauna in a balanced state. Nature balances stream life by maintaining both the number and the type of species present in any one part of the stream. Such balance ensures that there is never an overabundance of one species compared to another. Nature structures the stream environment so that both plant and animal life is dependent upon the existence of others within the stream.

As mentioned, lotic (washed) habitats are characterized by continuously running water or current flow. These running water bodies, have typically three zones: riffle, run, and pool. The riffle zone contains faster flowing, well-oxygenated water with coarse sediments. In the riffle zone, the velocity of current is great enough to keep the bottom clear of silt and sludge, providing a firm bottom for organisms. This zone contains specialized organisms that are adapted to live in running water. For example, organisms adapted to live in fast streams or rapids (trout) have streamlined bodies that aid in their respiration and in ability to obtain food.[15] Stream organisms that live under rocks to avoid the strong current have flat or streamlined bodies. Others have hooks or suckers to cling or attach to a firm substrate to avoid the washing-away effect of the strong current.

The run zone (or intermediate zone) is the slow-moving, relatively shallow part of the stream with moderately low velocities and little or no surface turbulence.

The pool zone of the stream is usually a deeper water region where velocity of water is reduced and silt and other settling solids provide a soft bottom (more homogeneous sediments) that is unfavorable for sensitive bottom-dwellers. Decomposition of some these solids cause a lower amount of DO. Some stream organisms spend some of their time in the rapids part of the stream and other times can be found in the pool zone. For example, trout typically spend about the same amount of time in the rapid zone pursuing food as they do in the pool zone pursuing shelter.

Organisms are sometimes classified based on their mode of life.

1. Benthos (mud dwellers) — The term originates from the Greek word for bottom and broadly includes aquatic organisms living on the bottom or on submerged vegetation. They live under and on rocks and in the sediments. A shallow sandy bottom has sponges, snails, earthworms, and some insects. A deep, muddy bottom will support clams; crayfish; and nymphs of damselflies, dragonflies, and mayflies. A firm, shallow, rocky bottom has nymphs of mayflies, stoneflies, and larvae of water beetles.
2. Periphytons or aufwuchs — The first term usually refers to microfloral growth upon substrata (i.e., benthic-attached algae). The second term, aufwuchs (pronounce: OWF-vooks; German: growth upon), refers to the fuzzy, sort of furry-looking, slimy green coating that attach or cling to stems and leaves of rooted plants or other objects projecting above the bottom without penetrating the surface. It consists not only of algae like Chlorophyta, but also diatoms, protozoa, bacteria, and fungi.
3. Planktons (drifters) — They are small, mostly microscopic plants and animals that are suspended in the water column; movement

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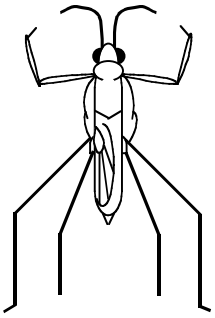

FIGURE 12.13 Water strider. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

depends on water currents. They mostly float in the direction of current. There are two types of planktons. The first type, phytoplanktons, are assemblages of small plants (algae) and have limited locomotion abilities; they are subject to movement and distribution by water movements. The second type, zooplanktons are animals that are suspended in water and have limited means of locomotion. Examples of zooplanktons include crustaceans, protozoans, and rotifers.

4. Nektons or pelagic organisms (capable of living in open waters) — They are distinct from other planktons in that they are capable of swimming independently of turbulence. They are swimmers that can navigate against the current. Examples of nektons include fish, snakes, diving beetles, newts, turtles, birds, and large crayfish.
5. Neustons — They are organisms that float or rest on the surface of the water (never break water tension). Some varieties can spread out their legs so that the surface tension of the water is not broken (e.g., water striders) (see Figure 12.13).
6. Madricoles — They are organisms that live on rock faces in waterfalls or seepages.

In a stream, the rocky substrate is the home for many organisms. Thus, we need to know something about the particles that make up the substrate. Namely, we need to know how to measure the particles so we can classify them by size.

Substrate particles are measured with a metric ruler, in centimeters. Because rocks can be long and narrow, we measure them twice: first the width, then the length. By adding the width to the length and dividing by two, we obtain the average size of the rock.

It is important to randomly select the rocks we wish to measure. Otherwise, we would tend to select larger rocks, more colorful rocks, or those with unusual shapes. Instead, we should just reach down and collect those rocks in front of us and within easy reach and then measure each rock. Upon completion of measurement, each rock should be classified. Ecologists have developed a standard scale (Wentworth scale) for size categories of substrate rock and other mineral materials, along with the different sizes:

Boulder	>256 mm
Cobble	64–256 mm
Pebble	16–64 mm
Gravel	2–16 mm
Sand	0.0625–2 mm
Silt	0.0039–0.0625 mm
Clay	<0.0039 mm

Organisms that live in, on, or under rocks or small spaces occupy what is known as a *microhabitat*. Some organisms make their own microhabitats: many of the caddisflies build a case about them and use it for their shelter.

Rocks are not the only physical features of streams where aquatic organisms can be found. For example, fallen logs and branches (commonly referred to as large woody debris), provide an excellent place for some aquatic organisms to burrow into and surfaces for others to attach themselves, as they might to a rock. They also create areas where small detritus, such as leaf litter, can pile up underwater. These piles of leaf litter are excellent shelters for many organisms, including large, fiercely predaceous larvae of dobsonflies.

Another important aquatic organism habitat is found in the matter, or drift, that floats along down stream. Drift is important because it is the main source of food for many fish. It may include insects such as mayflies (Ephemeroptera), some true flies (Diptera) and some stoneflies (Plecoptera), and caddisflies (Trichoptera). In addition, dead or dying insects and other small organisms, terrestrial insects that fall from the trees, leaves, and other matter are common components of drift. Among the crustaceans, amphipods (small crustaceans) and isopods (small crustaceans including sow bugs and gribbles) also have been reported in the drift.

12.11.9 Adaptations to Stream Current

Current in streams is the outstanding feature of streams and the major factor limiting the distribution of organisms. The current is determined by the steepness of the bottom gradient, the roughness of the streambed, and the depth and width of the streambed. The current in streams has promoted many special adaptations by stream organisms. Odum lists the following adaptations (see Figure 12.14):[16]

1. Attachment to a firm substrate — Attachment is to stones, logs, leaves, and other underwater objects, such as discarded tires, bottles, pipes, etc. Organisms in this group are primarily composed

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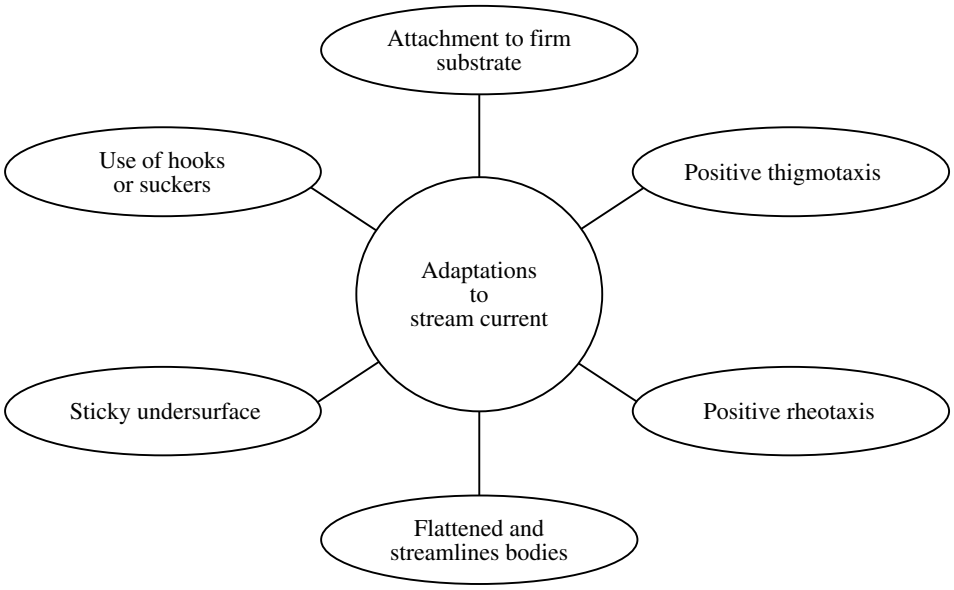

FIGURE 12.14 Adaptations to stream current. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

of the primary producer plants and animals, such as green algae, diatoms, aquatic mosses, caddisfly larvae, and freshwater sponges.

2. The use of hooks and suckers — These organisms have the unusual ability to remain attached and withstand even the strongest rapids. Two Diptera larvae, Simulium and Blepharocera, are examples.
3. A sticky undersurface — Snails and flatworms are examples of organisms that are able to use their sticky undersurfaces to adhere to underwater surfaces.
4. Flattened and streamlined bodies — All macroconsumers have streamlined bodies (i.e., the body is broad in front and tapers posteriorly to offer minimum resistance to the current). All nektons, such as fish, amphibians, and insect larvae, exhibit this adaptation. Some organisms have flattened bodies that enable them to stay under rocks and in narrow places. Examples are water penny, a beetle larva, mayfly, and stone fly nymphs.
5. Positive rheotaxis (rheo: current; taxis: arrangement) — An inherent behavioral trait of stream animals (especially those capable of swimming) is to orient themselves upstream and swim against the current.
6. Positive thigmotaxis (thigmo: touch, contact) — Another inherent behavior pattern for many stream animals is to cling close to a surface or keep the body in close contact with the surface. This is the reason that stonefly nymphs (when removed from one environment and placed into another) will attempt to cling to just about anything, including each other.

It would take an entire text to describe the great number of adaptations made by aquatic organisms to their surroundings in streams. For our purposes, instead, we cover those special adaptations that are germane to this discussion. The important thing to remember is that there are several basic ways for an aquatic organism to adapt to its environment.

12.11.10 Types of Adaptive Changes

Adaptive changes are classed as genotypic, phenotypic, behavioral, or ontogenic.

1. Genotypic changes — Tend to be great enough to separate closely related animals into species, such as mutations or recombination of genes. A salmonid is an example that has evolved a subterminal mouth (i.e., below the snout) in order to eat from the benthos.
2. Phenotypic changes — These are the changes that an organism might make during its lifetime to better utilize its environment (e.g., a fish that changes sex from female to male because of an absence of males).
3. Behavioral changes — These changes have little to do with body structure or type: a fish might spend more time under an overhang to hide from predators.
4. Ontogenetic change — This change takes place as an organism grows and matures (e.g., a coho

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salmon that inhabits streams when young and migrates to the sea when older, changing its body chemistry to allow it to tolerate saltwater).

12.11.11 Specific Adaptations

Specific adaptations observed in aquatic organisms include mouths, shape, color, aestivation, and schooling.

1. Mouths — Aquatic organisms, such as fish, change mouth shape (morphology) depending on the food the fish eats. The arrangement of the jawbones and even other head bones; the length and width of gill rakers; the number, shape, and location of teeth; and barbels all change to allow fish to eat just about anything found in a stream.
2. Shape — An aquatic organism's shape changes to allow fish to do different things in the water. Some organisms have body shapes that push them down in the water, against the substrate, and allow them to hold their place against even strong current (e.g., chubs, catfish, dace, and sculpins). Other organisms, especially predators, have evolved an arrangement and shape of fins that allows them to lurk without moving as they lunge suddenly to catch their prey (e.g., bass, perch, pike, trout, and sunfish).
3. Color — This may change within hours, to camouflage, or within days, or may be genetically predetermined. Fish tend to turn dark in clear water and pale in muddy water.
4. Aestivation — This helps fishes survive in arid desert climates, where streams may dry up from time to time. Aestivation refers to the ability of some fishes to burrow into the mud and wait out the dry period.
5. Schooling — This serves as protection for many fish, particularly those that are subject to predation.

12.12 BENTHIC LIFE: AN OVERVIEW

The benthic habitat is found in the streambed, or benthos. As mentioned, the streambed is comprised of various physical and organic materials where erosion and deposition are a continuous characteristic. Erosion and deposition may occur simultaneously and alternately at different locations in the same streambed. Where channels are exceptionally deep and taper slowly to meet the relatively flattened streambed, habitats may form on the slopes of the channel. These habitats are referred to as littoral habitats. Shallow channels may dry up periodically in accordance with weather changes. The streambed is then exposed to open air and may take on the characteristics of a wetland.

Silt and organic materials settle and accumulate in the streambed of slowly flowing streams. These materials decay and become the primary food resource for the invertebrates inhabiting the streambed. Productivity in this habitat depends upon the breakdown of these organic materials by herbivores. Bottom dwelling organisms do not completely use all-organic materials; a substantial amount becomes part of the streambed in the form of peat.

In faster moving streams, organic materials do not accumulate so easily. Primary production occurs in a different type of habitat found in the riffle regions where there are shoals and rocky regions for organisms to adhere. Therefore, plants that can root themselves into the streambed dominate these regions. When referring to plants we are referring mostly to forms of algae, often microscopic and filamentous, that can cover rocks and debris that have settled into the streambed during summer months.

Note: If you have ever stepped into a stream, the green, slippery slime on the rocks in the streambed is representative of this type of algae.

Although the filamentous algae seem well anchored, strong currents can easily lift it from the streambed and carry it downstream where it becomes a food resource for low-level consumers. One factor that greatly influences the productivity of a stream is the width of the channel; a direct relationship exists between stream width and richness of bottom organisms. Bottom dwelling organisms are very important to the ecosystem as they provide food for other, larger benthic organisms through consuming detritus.

12.12.1 Benthic Plants and Animals

Vegetation is not common in the streambed of slow moving streams, but they may anchor themselves along the banks. Alga (mainly green and blue-green) as well as common types of water moss attaches to rocks in fast moving streams. Mosses and liverworts often climb up the sides of the channel onto the banks as well. Some plants similar to the reeds of wetlands with long stems and narrow leaves are able to maintain roots and withstand the current.

Aquatic insects and invertebrates dominate slow moving streams. Most aquatic insects are in their larval and nymph forms, such as the blackfly, caddisfly, and stonefly. Adult water beetles and waterbugs are also abundant. Insect larvae and nymphs provide the primary food source for many fish species, including American eel and brown bullhead catfish. Representatives of crustaceans, rotifers, and nematodes (flat worms) are sometimes present. Leech, worm, and mollusk (especially freshwater mussels) abundance varies with stream conditions, but generally favors low phosphate conditions. Larger animals found in slow moving streams and rivers include newts, tadpoles, and

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frogs. As mentioned, the important characteristic of all life in streams is adaptability to withstand currents.

12.13 BENTHIC MACROINVERTEBRATES

The emphasis on aquatic insect studies, which has expanded exponentially in the last three decades, has been largely ecological. Freshwater macroinvertebrates are ubiquitous; even polluted waters contain some representative of this diverse and ecologically important group of organisms.

Benthic macroinvertebrates are aquatic organisms without backbones that spend at least a part of their life cycle on the stream bottom. Examples include aquatic insects, such as stoneflies, mayflies, caddisflies, midges, and beetles, as well as crayfish, worms, clams, and snails. Most hatch from eggs and mature from larvae to adults. The majority of the insects spends their larval phase on the river bottom, and after a few weeks to several years, emerges as winged adults. The aquatic beetles, true bugs, and other groups remain in the water as adults. Macroinvertebrates typically collected from the stream substrate are either aquatic larvae or adults.

In practice, stream ecologists observe indicator organisms and their responses (biomonitoring; see Chapter 14) to determine the quality of the stream environment. There are a number of methods for determining water quality based on biologic characteristics. A wide variety of indicator organisms (biotic groups) is used for biomonitoring. The most often used include algae, bacteria, fish, and macroinvertebrates.

Notwithstanding their popularity, in this text we use benthic macroinvertebrates for a number of other reasons. Simply, they offer a number of advantages:

1. They are ubiquitous, so they are affected by perturbations in many different habitats.
2. They are species rich, so the large number of species produces a range of responses.
3. They are sedentary, so they stay put, which allows determination of the spatial extent of a perturbation.
4. They are long-lived, which allows temporal changes in abundance and age structure to be followed.
5. They integrate conditions temporally, so like any biotic group, they provide evidence of conditions over long periods.

In addition, benthic macroinvertebrates are preferred as bioindicators because they are easily collected and handled by samplers; they require no special culture protocols. They are visible to the naked eye and samplers easily distinguish their characteristics. They have a variety of fascinating adaptations to stream life. Certain benthic macroinvertebrates have very special tolerances that make them excellent specific indicators of water quality. Useful benthic macroinvertebrate data are easy to collect without expensive equipment. The data obtained by macroinvertebrate sampling can serve to indicate the need for additional data collection, possibly including water analysis and fish sampling.

In short, we base the focus of this discussion on benthic macroinvertebrates (in regards to water quality in streams and lakes) simply because some cannot survive in polluted water while others can survive or even thrive in polluted water. In a healthy stream, the benthic community includes a variety of pollution-sensitive macroinvertebrates. In an unhealthy stream or lake, there may be only a few types of nonsensitive macroinvertebrates present. The presence or absence of certain benthic macroinvertebrates is an excellent indicator of water quality.

It may also be difficult to identify stream or lake pollution with water analysis, which can only provide information for the time of sampling (a snapshot of time). Even the presence of fish may not provide information about a polluted stream because fish can move away to avoid polluted water and then return when conditions improve. Most benthic macroinvertebrates cannot move to avoid pollution. A macroinvertebrate sample may provide information about pollution that is not present at the time of sample collection.

Before anyone is able to use benthic macroinvertebrates to gauge water quality in a stream (or for any other reason), he must be familiar with the macroinvertebrates that are commonly used as bioindicators. Samplers need to be aware of basic insect structures before they can classify the macroinvertebrates they collect (see Chapter 14). Structures, which need to be stressed, include head, eyes (compound and simple), antennae, mouth (no emphasis on parts), segments, thorax, legs and leg parts, gills, abdomen, etc. Samplers also need to be familiar with insect metamorphosis — both complete and incomplete — as most of the macroinvertebrates collected are larval or nymph stages.

Note: Information on basic insect structures is beyond the scope of this text. Thus, we highly recommend "the" standard guide to aquatic insects of North America: *An Introduction to the Aquatic Insects of North America*, 3rd ed., Merritt, R.W. and Cummins, K.W., Eds., Kendall/Hunt Publishing Company, Dubuque, IA, 1996.

12.13.1 Identification of Benthic Macroinvertebrates

Before identifying and describing the key benthic macroinvertebrates significant to water and wastewater operators, it is important first to provide foundational information.

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We characterize benthic macroinvertebrates using two important descriptive classifications: trophic groups and mode of existence. In addition, we discuss their relationship in the food web, meaning what, or whom, they eat.

1. Trophic groups — Of the trophic groups (i.e., feeding groups) that Merritt and Cummins have identified for aquatic insects, only five are likely to be found in a stream using typical collection and sorting methods:[17]
   a. Shredders — These have strong, sharp mouthparts that allow them to shred and chew coarse organic material, such as leaves, algae, and rooted aquatic plants. These organisms play an important role in breaking down leaves or larger pieces of organic material to a size that can be used by other macroinvertebrates. Shredders include certain stonefly and caddisfly larvae, sowbugs, scuds, and others.
   b. Collectors — These gather the very finest suspended matter in the water. To do this, they often sieve the water through rows of tiny hairs. These sieves of hairs may be displayed in fans on their heads (blackfly larvae) or on their forelegs (some mayflies). Some caddisflies and midges spin nets and catch their food in them as the water flows through.
   c. Scrapers — These scrape the algae and diatoms off surfaces of rocks and debris, using their mouthparts. Many of these organisms are flattened to hold onto surfaces while feeding. Scrapers include water pennies, limpets and snails, netwinged midge larvae, certain mayfly larvae, and others.
   d. Piercers — These herbivores pierce plant tissues or cells and suck the fluids out. Some caddisflies do this.
   e. Predators — Predators eat other living creatures. Some of these are engulfers; they eat their prey completely or in parts. This is very common in stoneflies and dragonflies, as well as caddisflies. Others are piercers, which are like the herbivorous piercers except that they are eating live animal tissues.
2. Mode of existence (habit, locomotion, attachment, concealment):
   a. Skaters — Adapted for skating on the surface where they feed as scavengers on organisms trapped in the surface film (e.g., water striders).
   b. Planktonic — Inhabiting the open water limnetic zone of standing waters (lentic; lakes, bogs, ponds). Representatives may float and swim about in the open water, but usually exhibit a diurnal vertical migration pattern (e.g., phantom midges) or float at the surface to obtain oxygen and food, diving when alarmed (e.g., mosquitoes).
   c. Divers — Adapted for swimming by rowing with the hind legs in lentic habitats and lotic pools. Representatives come to the surface to obtain oxygen and dive and swim when feeding or alarmed; they may cling to or crawl on submerged objects such as vascular plants (e.g., water boatmen and predaceous diving beetle).
   d. Swimmers — Adapted for fishlike swimming in lotic or lentic habitats. Individuals usually cling to submerged objects, such as rocks (lotic riffles) or vascular plants (lentic), between short bursts of swimming (e.g., mayflies).
   e. Clingers — Representatives have behavioral (e.g., fixed retreat construction) and morphological (e.g., long, curved tarsal claws; dorsoventral flattening; and ventral gills arranged as a sucker) adaptations for attachment to surfaces in stream riffles and wave-swept rocky littoral zones of lakes (e.g., mayflies and caddisflies).
   f. Sprawlers — Inhabiting the surface of floating leaves of vascular hydrophytes or fine sediments, usually with modifications for staying on top of the substrate and maintaining the respiratory surfaces free of silt (e.g., mayflies, dobsonflies, and damselflies).
   g. Climbers — adapted for living on vascular hydrophytes or detrital debris (e.g., overhanging branches, roots and vegetation along streams, and submerged brush in lakes) with modifications for moving vertically on stem-type surfaces (e.g., dragonflies and damselflies).
   h. Burrowers — Inhabiting the fine sediments of streams (pools) and lakes. Some construct discrete burrows, which may have sand grain tubes extending above the surface of the substrate, or the individuals may ingest their way through the sediments (examples: mayflies and midges).

12.13.2 Macroinvertebrates and the Food Web

In a stream or lake, there are two possible sources of primary energy: (1) photosynthesis by algae, mosses, and higher aquatic plants, and (2) imported organic matter from streamside or lakeside vegetation (e.g., leaves and other parts of vegetation). Simply put, a significant portion of the food that is eaten grows right in the stream or lake, such as algae, diatoms, nymphs and larvae, and fish. A

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food that originates from within the stream is called autochthonous.

Most food in a stream comes from outside the stream. This is especially the case in small, heavily wooded streams where there is normally insufficient light to support substantial instream photosynthesis so energy pathways are supported largely by imported energy. Leaves provide a large portion of this imported energy. Worms drown in floods and are washed in. Leafhoppers and caterpillars fall from trees. Adult mayflies and other insects mate above the stream, lay their eggs in it, and then die in it. All of this food from outside the stream is called allochthonous.

12.13.3 Units of Organization

Macroinvertebrates, like all other organisms, are classified and named. Macroinvertebrates are classified and named using a taxonomic hierarchy. The taxonomic hierarchy for the caddisfly (a macroinvertebrate insect commonly found in streams) is shown below.

Kingdom:	Animalia (animals)
Phylum:	Arthropoda ("jointed legs")
Class:	Insecta (insect)
Order:	Trichoptera (caddisfly)
Family:	Hydropsychidae (net-spinning caddis)
Genus species:	*Hydropsyche morosa*

12.13.4 Typical Running Water Benthic Macroinvertebrates

As mentioned, the macroinvertebrates are the best-studied and most diverse animals in streams. We therefore devote our discussion to the various macroinvertebrate groups.

While it is true that non-insect macroinvertebrates, such as Oligochaeta (worms), Hirudinea (leeches), and Acari (water mites), are frequently encountered groups in lotic environments, the insects are among the most conspicuous inhabitants of streams. In most cases, it is the larval stages of these insects that are aquatic, whereas the adults are terrestrial. Typically, the larval stage is much extended, while the adult lifespan is short. Lotic insects are found among many different orders, and brief accounts of their biology are presented in the following sections.

12.14 INSECT MACROINVERTEBRATES

The most important insects groups in streams are Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Diptera (true flies), Coleoptera (beetles), Hemiptera (bugs), Megaloptera (alderflies and dobsonflies), and Odonata (dragonflies and damselflies). The identification of these different orders is usually easy and there are many keys and specialized references (e.g., Merritt and Cummins, *An Introduction to the Aquatic Insects of North America*, 1996) available to help in the identification to species. In contrast, there are some genera and species that specialist taxonomists can often only diagnose particularly the Diptera.

As mentioned, insect macroinvertebrates are ubiquitous in streams and are often represented by many species. Although the numbers refer to aquatic species, a majority is to be found in streams.

12.14.1 Mayflies (Order: Ephemeroptera)

Streams and rivers are generally inhabited by many species of mayflies, and most species are restricted to streams. For the experienced freshwater ecologist who looks upon a mayfly nymph, recognition is obtained through trained observation: abdomen with leaf-like or feather-like gills, legs with a single tarsal claw, and generally with three cerci (three tails; two cerci, and between them usually a terminal filament; see Figure 12.15). The experienced ecologist knows that mayflies are hemimetabolous insects (i.e., where larvae or nymphs resemble wingless adults) that go through many postembryonic molts, often in the range between 20 and 30. For some species, body length increases about 15% for each instar.

Mayfly nymphs are mainly grazers or collector-gatherers feeding on algae and fine detritus, although a few genera are predatory. Some members filter particles from the water using hair-fringed legs or maxillary palps. Shredders are rare among mayflies. In general, mayfly nymphs tend to live mostly in unpolluted streams, where with densities of up to 10,000/m^2, they contribute substantially to secondary producers.

Adult mayflies resemble nymphs, but usually possess two pair of long, lacy wings folded upright; adults usually have only two cerci. The adult lifespan is short, ranging from a few hours to a few days and rarely up to two weeks, and the adults do not feed. Mayflies are unique among insects in having two winged stages: the subimago and the imago. The emergence of adults tends to be synchronous, thus ensuring the survival of enough adults to continue the species.

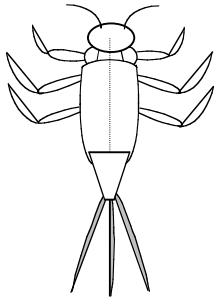

FIGURE 12.15 Mayfly (Order: Emphemeroptera). (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

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12.14.2 Stoneflies (Order: Plecoptera)

Although many freshwater ecologists would maintain that the stonefly is a well-studied group of insects, this is not exactly the case. Despite their importance, less than 5 to 10% of stonefly species are well known with respect to life history, trophic interactions, growth, development, spatial distribution, and nymphal behavior.

Despite our lack of extensive knowledge of stoneflies, enough is known to provide an accurate characterization of these aquatic insects. We know, for example, that stonefly larvae are characteristic inhabitants of cool, clean streams (i.e., most nymphs occur under stones in well-aerated streams). While they are sensitive to organic pollution, or more precisely to low oxygen concentrations accompanying organic breakdown processes, stoneflies seem rather tolerant to acidic conditions. Lack of extensive gills partly explains their relative intolerance of low oxygen levels.

Stoneflies are drab-colored, small- to medium-sized (1/6 to 2¼ in. [4 to 60 mm]), rather flattened insects. Stoneflies have long, slender, multi-segmented antennae and two long narrow antenna-like structures (cerci) on the tip of the abdomen (see Figure 12.16). The cerci may be long or short. At rest, the wings are held flat over the abdomen, giving a square-shouldered look compared to the roof-like position of most caddisflies and vertical position of the mayflies. Stoneflies have two pair of wings. The hind wings are slightly shorter than the forewings and much wider, having a large anal lobe that is folded fanwise when the wings are at rest. This fanlike folding of the wings gives the order its name: pleco (folded or plaited) and -ptera (wings). The aquatic nymphs are generally very similar to mayfly nymphs except that they have only two cerci at the tip of the abdomen. The stoneflies have chewing mouthparts. They may be found anywhere in a nonpolluted stream where food is available. Many adults do not feed and have reduced or vestigial mouthparts.

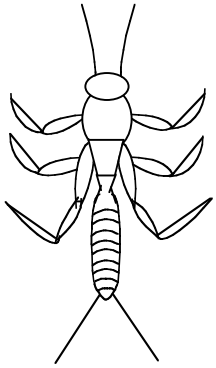

FIGURE 12.16 Stonefly (Order: Plecoptera). (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

Stoneflies have a specific niche in high quality streams where they are very important as a fish food source at specific times of the year (winter to spring, especially) and of the day. They complement other important food sources, such as caddisflies, mayflies, and midges.

12.14.3 Caddisflies (Order: Trichoptera)

Trichoptera (Greek: trichos, a hair; ptera, wing), are one of the most diverse insect orders living in the stream environment, and caddisflies have nearly a worldwide distribution (the exception: Antarctica). Caddisflies may be categorized broadly into free-living (roving and net spinning) and case-building species.

Caddisflies are described as medium-sized insects with bristle-like and often long antennae. They have membranous hairy wings (explains the Latin name "Trichos") that are held tent-like over the body when at rest; most are weak fliers. They have greatly reduced mouthparts and five tarsi. The larvae are mostly caterpillar like and have a strongly sclerotized (hardened) head with very short antennae and biting mouthparts. They have well-developed legs with a single tarsi. The abdomen is usually 10-segmented. In case-bearing species, the first segment bears 3 papillae, 1 dorsally and the other 2 laterally. This helps hold the insect centrally in its case, allowing a good flow of water passed the cuticle and gills; the last or anal segment bears a pair of grappling hooks.

In addition to being aquatic insects, caddisflies are superb architects. Most caddisfly larvae (see Figure 12.17) live in self-designed, self-built houses called cases. They spin out silk, and either live in silk nets or use the silk to stick together bits of whatever is lying on the stream bottom. These houses are so specialized, that you can usually identify a caddisfly larva to genus if you can see its house (case). With nearly 1400 species of caddisfly species in North America (north of Mexico), this is a good thing!

Caddisflies are closely related to butterflies and moths (order: Lepidoptera). They live in most stream habitats, which attributes to their diversity (have so many species). Each species has special adaptations that allow it to live in the environment it is found.

Mostly herbivorous, most caddisflies feed on decaying plant tissue and algae. Their favorite algae are diatoms, which they scrape off rocks. Some of them are predacious.

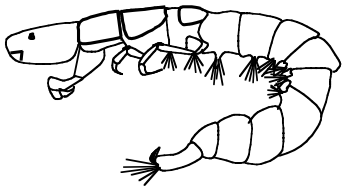

FIGURE 12.17 Caddis larvae, *Hydropsyche* spp. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

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Caddisfly larvae can take a year or two to change into adults. They then change into pupae (the inactive stage in the metamorphosis of many insects, following the larval stage and preceding the adult form) while still inside their cases for their metamorphosis. It is interesting to note that caddisflies, unlike stoneflies and mayflies, go through a complete metamorphosis.

Caddisflies remain as pupae for 2 to 3 weeks, then emerge as adults. When they leave their pupae, splitting their case, they must swim to the surface of the water to escape it. The winged adults fly evening and night, and some are known to feed on plant nectar. Most of them will live less than 1 month: like many other winged stream insects, their adult lives are brief compared to the time they spend in the water as larvae.

Caddisflies are sometimes grouped by the kinds of cases they make into five main groups:

1. Free-living forms that do not make cases
2. Saddle-case makers
3. Purse-case makers
4. Net-spinners and retreat-makers
5. Tube-case makers

Caddisflies demonstrate their architectural talents in the cases they design and make. For example, a caddisfly might make a perfect, four-sided box case of bits of leaves and bark, or tiny bits of twigs. It may make a clumsy dome of large pebbles. Others make rounded tubes out of twigs or very small pebbles. In our experience in gathering caddisflies, we have come to appreciate not only their architectural ability, but also their flare in the selection of construction materials. For example, we have found many caddisfly cases constructed of silk, emitted through an opening at the tip of the labium, used together with bits of ordinary rock mixed with sparkling quartz and red garnet, green peridot, and bright fool's gold.

Besides the protection their cases provide them, the cases provide another advantage. The cases actually help caddisflies breathe. They move their bodies up and down and back and forth inside their cases, making a current that brings them fresh oxygen. The less oxygen there is in the water, the faster they have to move. It has been seen that caddisflies inside their cases get more oxygen than those that are outside of their cases. This is why stream ecologists think that caddisflies can often be found even in still waters, where dissolved oxygen is low, in contrast to stoneflies and mayflies.

12.14.4 True Flies (Order: Diptera)

True or two- (di-) winged (ptera) flies not only include the flies that we are most familiar with, like fruitflies and houseflies, but they also include midges (see Figure 12.18), mosquitoes, craneflies (see Figure 12.19), and others. Houseflies and fruitflies live only on land, and we do not concern ourselves with them. Some spend nearly their whole lives in water; they contribute to the ecology of streams.

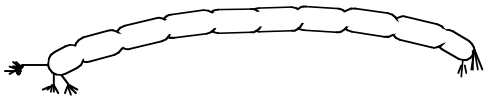

FIGURE 12.18 Midge larvae. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

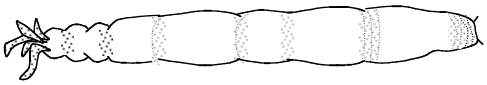

FIGURE 12.19 Cranefly larvae. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

True flies are in the order Diptera, and are one of the most diverse orders of the class Insecta, with about 120,000 species worldwide. Dipteran larvae occur almost everywhere except Antarctica and deserts where there is no running water. They may live in a variety of places within a stream: buried in sediments, attached to rocks, beneath stones, in saturated wood or moss, or in silken tubes that are attached to the stream bottom. Some even live below the stream bottom.

True fly larvae may eat almost anything, depending on their species. Those with brushes on their heads use them to strain food out of the water that passes through. Others may eat algae, detritus, plants, and even other fly larvae.

The longest part of the true fly's life cycle, like that of mayflies, stoneflies, and caddisflies, is the larval stage. It may remain an underwater larva anywhere from a few hours to 5 years. The colder the environment, the longer it takes to mature. It pupates and emerges and then becomes a winged adult. The adult may live 4 months — or it may only live for a few days. While reproducing, it will often eat plant nectar for the energy it needs to make its eggs. Mating sometimes takes place in aerial swarms. The eggs are deposited back in the stream; some females will crawl along the stream bottom, losing their wings, to search for the perfect place to put their eggs. Once they lay them, they die.

Diptera serve an important role in cleaning water and breaking down decaying material, and they are also a vital food source (i.e., they play pivotal roles in the processing of food energy) for many of the animals living in and around streams. The true flies most familiar to us are the midges, mosquitoes, and the craneflies because they are pests. Some midge flies and mosquitoes bite; the cranefly, does not bite but looks like a giant mosquito.

Like mayflies, stoneflies, and caddisflies, true flies are mostly in larval form. Like caddisflies, you can also find their pupae because they are holometabolous insects (go

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through complete metamorphosis). Most of them are free-living, meaning they can travel around. Although none of the true fly larvae have the six, jointed legs we see on the other insects in the stream, they sometimes have strange little almost-legs — prolegs — to move around.

Others may move somewhat like worms do, and some — the ones who live in waterfalls and rapids — have a row of six suction discs that they use to move much like a caterpillar does. Many use silk pads and hooks at the ends of their abdomens to hold them fast to smooth rock surfaces.

12.14.5 Beetles (Order: Coleoptera)[18]

Of the more than 1 million described species of insect, at least 1/3 are beetles, making the Coleoptera not only the largest order of insects but also the most diverse order of living organisms. Even though they are the most speciose order of terrestrial insects, their diversity is not so apparent in running waters. Coleoptera belongs to the infraclass Neoptera, division Endpterygota. Members of this order have an anterior pair of wings (the elytra) that are hard and leathery and not used in flight; the membranous hind-wings, which are used for flight, are concealed under the elytra when the organisms are at rest. Only 10% of the 350,000 described species of beetles are aquatic.

Beetles are holometabolous. Eggs of aquatic coleopterans hatch in 1or 2 weeks, with diapause occurring rarely. Larvae undergo from 3 to 8 molts. The pupal phase of all coleopternas is technically terrestrial; making this life stage of beetles the only one that has not successfully invaded the aquatic habitat. A few species have diapausing prepupae, but most complete transformation to adults in 2 to 3 weeks. Terrestrial adults of aquatic beetles are typically short-lived and sometimes nonfeeding, like those of the other orders of aquatic insects. The larvae of Coleoptera are morphologically and behaviorally different from the adults, and their diversity is high.

Aquatic species occur in two major suborders: the Adephaga and the Polyphaga. Both larvae and adults of six beetle families are aquatic: Dytiscidae (predaceous diving beetles), Elmidae (riffle beetles), Gyrinidae (whirligig beetles), Halipidae (crawling water beetles), Hydrophilidae (water scavenger beetles), and Noteridae (burrowing water beetles). Five families, Chrysomelidae (leaf beetles), Limnichidae (marsh-loving beetles), Psephenidae (water pennies), Ptilodactylidae (toe-winged beetles), and Scirtidae (marsh beetles), have aquatic larvae and terrestrial adults, as do most of the other orders of aquatic insects; adult limnichids, readily submerge when disturbed. Three families have species that are terrestrial as larvae and aquatic as adults: Curculionidae (weevils), Dryopidae (long-toed water beetles), and Hydraenidae (moss beetles), a highly unusual combination among insects. (Note: Because they provide a greater understanding of a freshwater body's condition [i.e., they are useful indicators of water quality], we focus our discussion on the riffle beetle, water penny, and whirligig beetle.)

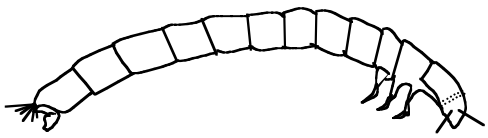

FIGURE 12.20 Riffle beetle larvae. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

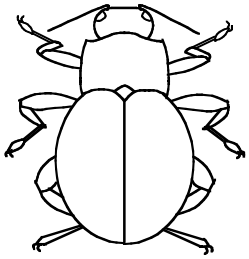

FIGURE 12.21 Riffle beetle adult. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

Riffle beetle larvae (most commonly found in running waters, hence the name riffle beetle) are up to 3/4 in. long (see Figure 12.20). Their body is not only long but also hard, stiff, and segmented. They have 6 long segmented legs on upper middle section of body; the back end has 2 tiny hooks and short hairs. Larvae may take 3 years to mature before they leave the water to form a pupa; adults return to the stream.

Riffle beetle adults are considered better indicators of water quality than larvae because they have been subjected to water quality conditions over a longer period. They walk very slowly under the water (on stream bottom), and do not swim on the surface. They have small oval-shaped bodies (see Figure 12.21) and are typically about ¾ in. in length.

Both adults and larvae of most species feed on fine detritus with associated microorganisms that is scraped from the substrate, although others may be xylophagous that is, (wood eating; e.g., Lara, Elmidae). Predators do not seem to include riffle beetles in their diet, except perhaps for eggs, which are sometimes attacked by flatworms.

The adult water penny is inconspicuous and often found clinging tightly in a sucker-like fashion to the undersides of submerged rocks, where they feed on attached algae. The body is broad, slightly oval, and flat in shape, ranging from 4 to 6 mm (1/4 in.) in length. The body is covered with segmented plates and looks like a tiny round leaf (see Figure 12.22). It has 6 tiny jointed legs (underneath). The color ranges from light brown to almost black.

There are 14 water penny species in the U.S. They live predominately in clean, fast-moving streams. Aquatic larvae live 1 year or more (they are aquatic); adults (they

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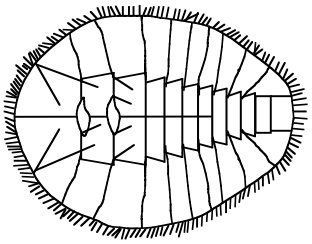

FIGURE 12.22 Water Penny larva. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

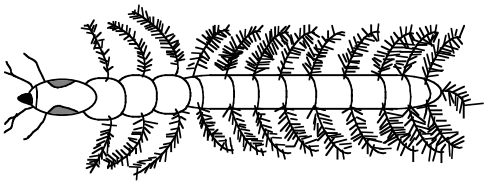

FIGURE 12.23 Whirligig beetle larva. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

are terrestrial) live on land for only a few days. They scrape algae and plants from surfaces.

Whirligig beetles are common inhabitants of streams and normally are found on the surface of quiet pools. The body has pincher-like mouthparts. Six segmented legs are on the middle of the body; the legs end in tiny claws. Many filaments extend from the sides of the abdomen. They have four hooks at the end of the body and no tail (see Figure 12.23).

Note: When disturbed, whirligig beetles swim erratically or dive while emitting defensive secretions.

As larvae, they are benthic predators, whereas the adults live on the water surface, attacking dead and living organisms trapped in the surface film. They occur on the surface in aggregations of up to thousands of individuals. Unlike the mating swarms of mayflies, these aggregations serve primarily to confuse predators. Whirligig beetles have other interesting defensive adaptations. For example, the Johnston's organ at the base of the antennae enables them to echolocate using surface wave signals; their compound eyes are divided into two pairs, one above and one below the water surface. This enables them to detect both aerial and aquatic predators; they also produce noxious chemicals that are highly effective at deterring predatory fish.

12.14.6 Water Strider (Jesus bugs; Order: Hemiptera)

It is fascinating to sit on a log at the edge of a stream pool and watch the drama that unfolds among the small water animals. Among the star performers in small streams are the water bugs. These are aquatic members of that large group of insects called the true bugs, most of which live on land. Unlike many other types of water insects, they do not have gills, but get their oxygen directly from the air.

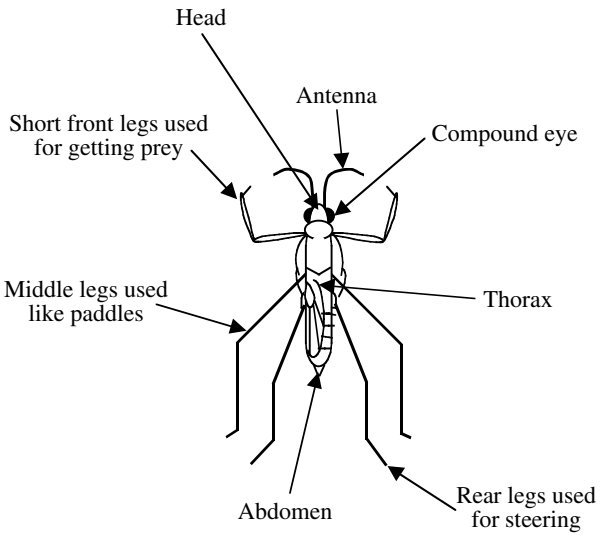

FIGURE 12.24 Water strider. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

Most conspicuous and commonly known are the Water Striders or Water Skaters. These ride the top of the water, with only their feet making dimples in the surface film. Like all insects, the water striders have a three-part body (head, thorax and abdomen), six jointed legs, and two antennae. It has a long, dark, narrow body (see Figure 12.24). The underside of the body is covered with water-repellent hair. Some water striders have wings, while others do not. Most water striders are over 0.2 in. (5 mm) long.

Water striders eat small insects that fall on the water's surface and larvae. Water striders are very sensitive to motion and vibrations on the water's surface. It uses this ability in order to locate prey. It pushes it mouth into its prey, paralyzes it, and sucks the insect dry. Predators of the water strider, like birds, fish, water beetles, backswimmers, dragonflies, and spiders, take advantage of the fact that water striders cannot detect motion above or below the water's surface.

12.14.7 Alderflies and Dobsonflies (Order: Megaloptera)

Larvae of all species of Megaloptera (large wing) are aquatic and attain the largest size of all aquatic insects. Megaloptera is a medium-sized order with less than 5000 species worldwide. Most species are terrestrial; in North America 64 aquatic species occur.

In running waters, alderflies (family: Sialidae) and dobsonflies (family: Corydalidae; sometimes called hellgrammites or toe biters) are particularly important, as

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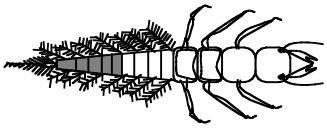

FIGURE 12.25 Alderfly larva. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

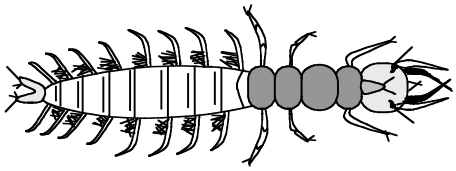

FIGURE 12.26 Dobsonfly larva. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

they are voracious predators, having large mandibles with sharp teeth.

Alderfly brownish-colored larvae possess a single tail filament with distinct hairs. The body is thick-skinned with six to eight filaments on each side of the abdomen; gills are located near the base of each filament. Mature body size: 0.5 to 1.25 in. (see Figure 12.25). Larvae are aggressive predators, feeding on other adult aquatic macroinvertebrates (they swallow their prey without chewing); as secondary consumers, other larger predators eat them. Female alderflies deposit eggs on vegetation that overhangs water, larvae hatch and fall directly into water (i.e., into quiet but moving water). Adult alderflies are dark with long wings folded back over the body; they only live a few days.

Dobsonfly larvae are extremely ugly (thus, they are rather easy to identify) and can be rather large, anywhere from 25 to 90 mm (1/3 in.) in length. The body is stout, with 8 pairs of appendages on the abdomen. Brush-like gills at base of each appendage look like hairy armpits (see Figure 12.26). The elongated body has spiracles (spines) and has 3 pairs of walking legs near the upper body and one pair of hooked legs at the rear. The head bears four segmented antennae, small compound eyes, and strong mouth parts (large chewing pinchers). Coloration varies from yellowish, brown, gray, and black, often mottled. Dobsonfly larvae, commonly known as hellgrammites, are customarily found along stream banks under and between stones. As indicated by the mouthparts, they are predators and feed on all kinds of aquatic organisms.

12.14.8 Dragonflies and Damselflies (Order: Odonata)

The Odonata (dragonflies, suborder Anisoptera; and damselflies, suborder Zygoptera) is a small order of conspicuous, hemimetabolous insects (lack a pupal stage) of about 5,000 named species and 23 families worldwide. Odonata is a Greek word meaning toothed one. It refers to the serrated teeth located on the insect's chewing mouthparts (mandibles).

Characteristics of dragonfly and damselfly larvae include:

1. Large eyes
2. Three pairs of long segmented legs on the upper middle section (thorax) of body
3. Large scoop-like lower lip that covers bottom of mouth
4. No gills on sides or underneath of abdomen

Note: Dragonflies and damselflies are unable to fold their four elongated wings back over the abdomen when at rest.

Dragonflies and damselflies are medium to large insects with two pairs of long equal sized wings. The body is long and slender, with short antennae. Immature stages are aquatic and development occurs in three stages (egg, nymph, adult).

Dragonflies are also known as darning needles. (Note: Myths about dragonflies warned children to keep quiet or else the dragonfly's darning needles would sew the child's mouth shut.) The nymphal stage of dragonflies is grotesque creatures, robust and stoutly elongated. They do not have long tails (see Figure 12.27). They are commonly gray, greenish, or brown to black in color. They are medium to large aquatic insects size ranging from 15 to 45 mm; their legs are short and used for perching. They are often found on submerged vegetation and at the bottom of streams in the shallows. They are rarely found in polluted waters. Food consists of other aquatic insects, annelids, small crustacea and mollusks. Transformation occurs when the nymph crawls out of the water, usually onto vegetation. There it splits its skin and emerges prepared for flight. The adult dragonfly is a strong flier, capable of great speed (>60 mi/h) and maneuverability. (They can fly backward, stop on a dime, zip 20 ft straight up, and slip sideways in the blink of an eye!) When at rest the wings remain open and out to the sides of the body.

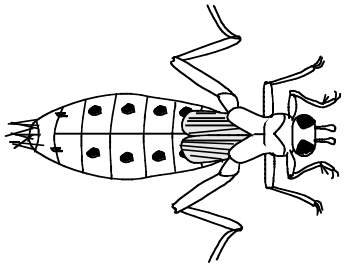

FIGURE 12.27 Dragonfly nymph. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

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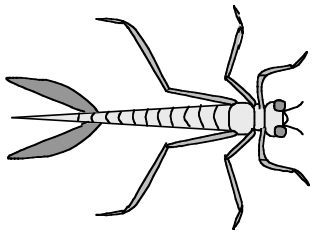

FIGURE 12.28 Damselfly nymph. (From Spellman, F.R., *Stream Ecology and Self-Purification,* Technomic Publ., Lancaster, PA, 1996.)

A dragonfly's freely movable head has large, hemispherical eyes (nearly 30,000 facets each) that are used to locate prey with their excellent vision. Dragonflies eat small insects, mainly mosquitoes (large numbers of mosquitoes), while in flight. Depending on the species, dragonflies lay hundreds of eggs by dropping them into the water and leaving them to hatch or by inserting eggs singly into a slit in the stem of a submerged plant. The incomplete metamorphosis (egg, nymph, mature nymph, and adult) can take 2 to 3 years. Nymphs are often covered by algal growth.

Note: Adult dragonflies are sometimes called "mosquito hawks" because they eat such a large number of mosquitoes that they catch while they are flying.

Damselflies are smaller and more slender than dragonflies. They have three long, oar-shaped feathery tails, which are actually gills, and long slender legs (see Figure 12.28). They are gray, greenish, or brown to black in color. Their habits are similar to those of dragonfly nymphs and emerge from the water as adults in the same manner. The adult damselflies are slow and seem uncertain in flight. Wings are commonly black or clear, and body is often brilliantly colored. When at rest, they perch on vegetation with their wings closed upright. Damselflies mature in 1 to 4 years. Adults live for a few weeks or months. Unlike the dragonflies, adult damselflies rest with their wings held vertically over their backs. They mostly feed on live insect larvae.

Note: Relatives of the dragonflies and damselflies are some of the most ancient of the flying insects. Fossils have been found of giant dragonflies with wingspans up to 720 mm that lived long before the dinosaurs!

12.15 NONINSECT MACROINVERTEBRATES

Note: Noninsect macroinvertebrates are important to our discussion of stream and freshwater ecology because many of them are used as bioindicators of stream quality; see Chapter 14.

Three frequently encountered groups in running water systems are Oligochaeta (worms), Hirudinea (leeches), and Gastropoda (lung-breathing snails). They are by no means restricted to running water conditions and the great majority of them occupy slow-flowing marginal habitats where the sedimentation of fine organic materials takes place.

12.15.1 Oligochaeta (Family: Tuificidae; Genus: Tubifex)

Tubifex worms (commonly known as sludge worms) are unique in the fact that they build tubes. Sometimes there are as many as 8000 individuals/m^2. They attach themselves within the tube and wave their posterior end in the water to circulate the water and make more oxygen available to their body surface. These worms are commonly red, since their blood contains hemoglobin. Tubifex worms may be very abundant in situations when other macroinvertebrates are absent; they can survive in very low oxygen levels and can live with no oxygen at all for short periods. They are commonly found in polluted streams, and feed on sewage or detritus.

12.15.2 Hirudinea (Leeches)

There are many different families of leeches, but all have common characteristics. They are soft-bodied worm-like creatures that are flattened when extended. Their bodies are dull in color, ranging from black to brown and reddish to yellow, often with a brilliant pattern of stripes or diamonds on the upper body. Their size varies within species but generally ranges from 5 mm to 45 cm when extended. Leeches are very good swimmers, but they typically move in an inchworm fashion. They are carnivorous and feed on other organisms that range from snails to warm-blooded animals. Leeches are found in warm protected shallows under rocks and other debris.

12.14.3 Gastropoda (Lung-Breathing Snail)

Lung-breathing snails (pulmonates) may be found in streams that are clean. However, their dominance may indicate that DO levels are low. These snails are different from right-handed snails because they do not breathe underwater by use of gills, but instead have a lung-like sac called a pulmonary cavity that they fill with air at the surface of the water. When the snail takes in air from the surface, it makes a clicking sound. The air taken in can enable the snail to breathe underwater for long periods, sometimes hours.

Lung-breathing snails have two characteristics that help us to identify them. First, they have no operculum or hard cover over the opening to their body cavity. Second, snails are either right-handed or left-handed, and the lung-breathing snails are left-handed. We can tell the difference

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by holding the shell so that its tip is upward and the opening is toward us. If the opening is to the left of the axis of the shell, the snail is termed sinistral, or left-handed. If the opening is to the right of the axis of the shell, the snail is termed dextral, or right-handed, and it breathes with gills. Snails are animals of the substrate and are often found creeping along on all types of submerged surfaces in water from 10 cm to 2 m deep.

Before the Industrial Revolution of the 1800s, metropolitan areas were small and sparsely populated. Thus, river and stream systems within or next to early communities received insignificant quantities of discarded waste. Early on, these river and stream systems were able to compensate for the small amount of wastes they received; when wounded (polluted), nature has a way of fighting back. In the case of rivers and streams, nature provides their flowing waters with the ability to restore themselves through their own self-purification process. It was only when humans gathered in great numbers to form great cities that the stream systems were not always able to recover from having received great quantities of refuse and other wastes. What exactly is it that man does to rivers and streams? Man upsets the delicate balance between pollution and the purification process, unbalancing the aquarium.

12.16 CHAPTER REVIEW QUESTIONS AND PROBLEMS

12.1. The major ecological unit is _____.

12.2. Those organisms residing within or on the bottom sediments are _____.

12.3. Organisms attached to plants or rocks are referred to as _____.

12.4. Small plants and animals that move about with the current are _____.

12.5. Free-swimming organisms belong to which group of aquatic organisms?

12.6. Organisms that live on the surface of the water are _____.

12.7. Movement of new individuals into a natural area is referred to as _____.

12.8. Fixes energy of the sun and makes food from simple inorganic substances _____.

12.9. The freshwater habitat that is characterized by normally calm water is _____,

12.10. The amount of oxygen dissolved in water and available for organisms is the _____.

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13 Water Quality

Are We to Wait Until All Frogs "Croak"?

> The earliest chorus of frogs — those high-pitched rhapsodies of spring peepers, those "jug-o-rum" calls of bullfrogs, those banjo-like bass harmonies of green frogs, those long and guttural cadences of leopard frogs, their singing a prelude to the splendid song of birds — beside an otherwise still pond on an early spring evening heralds one of nature's dramatic events: the drama of metamorphosis. This metamorphosis begins with masses of eggs that soon hatch into gill-breathing, herbivorous, fishlike tadpole larvae. As they feed and grow, warmed by the spring sun, almost imperceptibly a remarkable transformation begins. Hind legs appear and gradually lengthen. Tails shorten. Larval teeth vanish and lungs replace gills. Eyes develop lids. Forelegs emerge. In a matter of weeks, the aquatic, vegetarian tadpole will (should it escape the many perils of the pond) complete its metamorphosis into an adult, carnivorous frog.

This springtime metamorphosis is special: this anticipated event (especially for the frog) marks the end of winter, the rebirth of life, and a rekindling of hope (especially for mankind). This yearly miracle of change sums up in a few months each spring what occurred over 300 million years ago, when the frog evolved from its ancient predecessor. Today, however, something is different, strange, and wrong with this striking and miraculous event.

In the first place, where are all the frogs? Where have they gone? Why has their population decreased so dramatically in recent years?

The second problem: That this natural metamorphosis process (perhaps a reenactment of some Paleozoic drama whereby, over countless generations, the first amphibian-types equipped themselves for life on land) now demonstrates aberrations of the worst kind, of monstrous proportions and dire results to frog populations in certain areas. For example, reports have surfaced of deformed frogs in certain sections of the U.S., specifically Minnesota. Moreover, the U.S. Environmental Protection Agency (EPA) has received many similar reports from the U.S. and Canada as well as parts of Europe.

Most of the deformities have been in the rear legs and appear to be developmental. The question is: Why?

Researchers have noted that neurological abnormalities have also been found. Again, the question is why?

Researchers have pointed the finger of blame at parasites, pesticides, and other chemicals, ultraviolet radiation, acid rain, and metals. Something is going on. What is it? We do not know!

The next question becomes: What are we going to do about it? Are we to wait until all the frogs croak before we act — before we find the source, the cause, the polluter — before we see this reaction in other species; maybe in our own?

The final question is obvious: When frogs are forced by mutation into something else, is this evolution by gunpoint?

Is man holding the gun?[1]

13.1 INTRODUCTION

The quality of water, whether it is used for drinking, irrigation, or recreational purposes, is significant for health in both developing and developed countries worldwide. The first problem with water is rather obvious: A source of water must be found. Secondly, when accessible water is found it must be suitable for human consumption. Meeting the water needs of those that populate earth is an on-going challenge. New approaches to meeting these water needs will not be easy to implement: economic and institutional structures still encourage the wasting of water and the destruction of ecosystems.[2] Again, finding a water source is the first problem. Finding a source of water that is safe to drink is the other problem.

Water quality is important; it can have a major impact on health, both through outbreaks of waterborne disease and contributions to the background rates of disease. Accordingly, water quality standards are important to protect public health.

In this text, water quality refers to those characteristics or range of characteristics that make water appealing and useful. Keep in mind that useful also means nonharmful or nondisruptive to either ecology or the human condition within the very broad spectrum of possible uses of water. For example, the absences of odor, turbidity, or color are desirable immediate qualities. There are imperceptible qualities that are also important —the chemical qualities. The fact is the presence of materials, such as toxic metals (e.g., mercury and lead), excessive nitrogen and phosphorous, or dissolved organic material, may not be readily perceived by the senses, but may exert substantial negative impacts on the health of a stream and on human health. The ultimate impact of these imperceptible qualities of water (chemicals) on the user may be nothing more than loss of aesthetic values. On the other hand, water-containing

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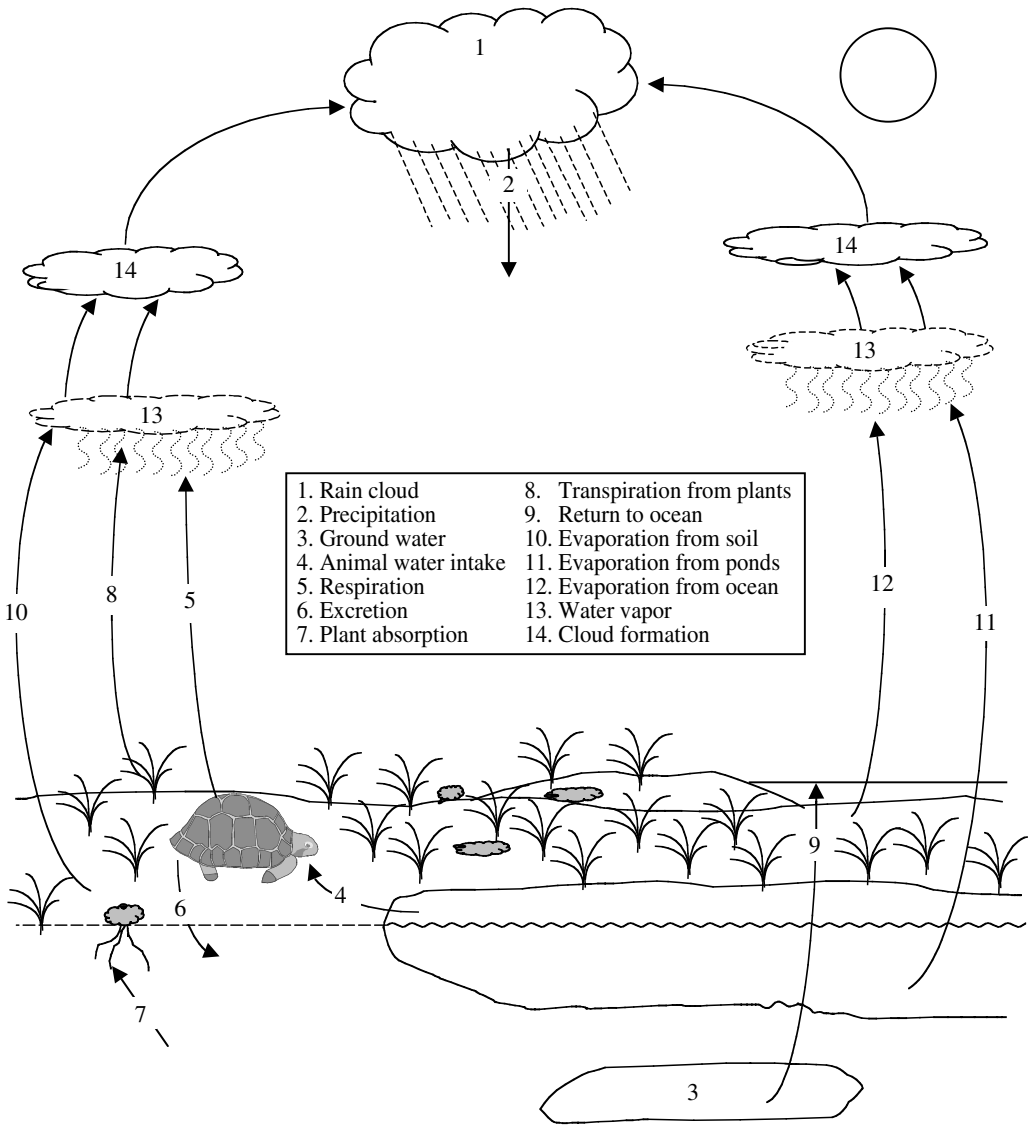

FIGURE 13.1 Water cycle. (From Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.)

chemicals could also lead to a reduction in biological health or to an outright degradation of human health.

Simply stated, the importance of water quality cannot be overstated.

In regards to water and wastewater treatment operations, water quality management begins with a basic understanding of how water moves through the environment, is exposed to pollutants, and transports and deposits pollutants. The hydrologic (water) cycle depicted by Figure 13.1 illustrates the general links among the atmosphere, soil, surface waters, groundwaters, and plants.

13.2 THE WATER CYCLE

Simply, the water cycle describes how water moves through the environment and identifies the links among groundwater, surface water, and the atmosphere (see Figure 13.1). As illustrated, water is taken from the earth's surface to the atmosphere by evaporation from the surface of lakes, rivers, streams, and oceans. This evaporation process occurs when the sun heats water. The sun's heat energizes surface molecules, allowing them to break free of the attractive force binding them together, and then evaporate and rise as invisible vapor in the atmosphere. Water vapor is also emitted from plant leaves by a process called *transpiration.* Every day, an actively growing plant transpires five to ten times as much water as it can hold at once. As water vapor rises, it cools and eventually condenses, usually on tiny particles of dust in the air. When it condenses, it becomes a liquid again or turns directly into a solid (ice, hail, or snow).

These water particles then collect and form clouds. The atmospheric water formed in clouds eventually falls to earth as precipitation. The precipitation can contain

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contaminants from air pollution. The precipitation may fall directly onto surface waters, be intercepted by plants or structures, or fall onto the ground. Most precipitation falls in coastal areas or in high elevations. Some of the water that falls in high elevations becomes runoff water, the water that runs over the ground (sometimes collecting nutrients from the soil) to lower elevations to form streams, lakes, and fertile valleys.

The water we see is known as surface water. Surface water can be broken down into five categories:

1. Oceans
2. Lakes
3. Rivers and streams
4. Estuaries
5. Wetlands

Because the amount of rain and snow remains almost constant, and population and usage per person are both increasing rapidly, water is in short supply. In the U.S. alone, water usage is 4 times greater today than it was in 1900. In the home, this increased use is directly related to an increase in the number of bathrooms, garbage disposals, home laundries, and lawn sprinklers. In industry, usage has increased 13 times since 1900.

There are 170,000+ small-scale suppliers that provide drinking water to approximately 200+ million Americans by 60,000+ community water supply systems, and to nonresidential locations, such as schools, factories, and campgrounds. The rest of Americans are served by private wells. The majority of the drinking water used in the U.S. is supplied from groundwater. Untreated water drawn from groundwater and surface waters and used as a drinking water supply can contain contaminants that pose a threat to human health.

Note: EPA reports that American households use approximately 146,000 gal of freshwater annually, drinking 1 billion glasses of tap water per day.[3]

With a limited amount of drinking water available for use, water that is available must be used and reused or we will be faced with an inadequate supply to meet the needs of all users. Water use and reuse is complicated by water pollution. Pollution is relative and hard to define. For example, floods and animals (dead or alive) are polluters, but their effects are local and tend to be temporary. Today, water is polluted in many sources, and pollution exists in many forms. It may appear as excess aquatic weeds; oil slicks; a decline in sport fishing; and an increase in carp, sludge worms, and other forms of life that readily tolerate pollution. Maintaining water quality is important because water pollution is not only detrimental to health, but also to recreation; commercial fishing; aesthetics; and private, industrial, and municipal water supplies.

At this point the reader may ask: With all the recent publicity about pollution and the enactment of new environmental regulations, has water quality in the U.S. improved recently? The answer is that with the recent pace of achieving fishable and swimmable waters under the Clean Water Act (CWA), one might think so.

In 1994, the *National Water Quality Inventory Report to Congress* indicated that 63% of the nation's lakes, rivers, and estuaries meet designated uses — only a slight increase over that reported in 1992.

The main culprit is nonpoint source pollution (NPS) (to be discussed in detail later). NPS is the leading cause of impairment for rivers, lakes, and estuaries. Impaired sources are those that do not fully support designated uses, such as fish consumption, drinking water supply, groundwater recharge, aquatic life support, or recreation. According to Fornter & Schechter, the five leading sources of water quality impairment in rivers are:

1. Agriculture
2. Municipal wastewater treatment plants
3. Habitat and hydrologic modification
4. Resource extraction
5. Urban runoff and storm sewers[4]

The health of rivers and streams is directly linked to the integrity of habitat along the river corridor and in adjacent wetlands. Stream quality will deteriorate if activities damage vegetation along riverbanks and in nearby wetlands. Trees, shrubs, and grasses filter pollutants from runoff and reduce soil erosion. Removal of vegetation also eliminates shade that moderates stream temperature. Stream temperature, in turn, affects the availability of dissolved oxygen (DO) in the water column for fish and other aquatic organisms.

Lakes, reservoirs, and ponds may receive water-carrying pollutants from rivers and streams, melting snow, runoff, or groundwater. Lakes may also receive pollution directly from the air.

In attempting to answer the original question about water quality improvement in the U.S., the best answer probably is that we are holding our own in controlling water pollution, but we need to make more progress. This understates an important point; when it comes to water quality, we need to make more progress on a continuing basis.

13.3 WATER QUALITY STANDARDS

The effort to regulate drinking water and wastewater effluent has increased since the early 1900s. Beginning with an effort to control the discharge of wastewater into the environment, preliminary regulatory efforts focused on protecting public health. The goal of this early wastewater treatment program was to remove suspended and floatable

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material, treat biodegradable organics, and eliminate pathogenic organisms. Regulatory efforts were pointed toward constructing wastewater treatment plants in an effort to alleviate the problem. Then a problem soon developed: progress. Time marched on and so did proliferation of city growth in the U.S. where it became increasingly difficult to find land required for wastewater treatment and disposal. Wastewater professionals soon recognized the need to develop methods of treatment that would accelerate nature's way (the natural purification of water) under controlled conditions in treatment facilities of comparatively smaller size.

Regulatory influence on water-quality improvements in both wastewater and drinking water took a giant step forward in the 1970s. The Water Pollution Control Act Amendments of 1972 (CWA), established national water pollution control goals. At about the same time, the Safe Drinking Water Act (SDWA) passed by Congress in 1974 started a new era in the field of drinking water supply to the public.

13.3.1 Clean Water Act (1972)

As mentioned, in 1972, Congress adopted the Clean Water Act (CWA), which establishes a framework for achieving its national objective "… to restore and maintain the chemical, physical, and biological integrity of the nation's waters." Congress decreed that, where attainable, water quality "… provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water." These goals are referred to as the "fishable and swimmable" goals of the act.

Before CWA, there were no specific national water pollution control goals or objectives. Current standards require that municipal wastewater be given secondary treatment (to be discussed in detail later) and that most effluents meet the conditions shown in Table 13.1. The goal, via secondary treatment (i.e., the biological treatment component of a municipal treatment plant), was set in order that the principal components of municipal wastewater, suspended solids, biodegradable material, and pathogens could be reduced to acceptable levels. Industrial dischargers are required to treat their wastewater to the level obtainable by the best available technology (BAT) for wastewater treatment in that particular type of industry.

In addition, a National Pollutant Discharge Elimination System (NPDES) program was established based on uniform technological minimums with which each point source discharger has to comply. Under NPDES, each municipality and industry discharging effluent into streams is assigned discharge permits. These permits reflect the secondary treatment and BAT standards.

Water quality standards are the benchmark against which monitoring data are compared to assess the health of waters to develop total maximum daily loads in impaired waters. They are also used to calculate water-quality-based discharge limits in permits issued under NPDES.

TABLE 13.1
Minimum National Standards for Secondary Treatment

Characteristic of Discharge	Unit of Measure	Average 30-day Concentration	Average 7-day Concentration
BOD	mg/L	30	45
Suspended solids	mg/L	30	45
Concentration	pH units	6.0–9.0	6.0–9.0

Source: Federal Register, Secondary Treatment Regulations, 40 CFR Part 133, 1988.

13.3.2 Safe Drinking Water Act (1974)

The SDWA of 1974 mandated EPA to establish drinking-water standards for all public water systems serving 25 or more people or having 15 or more connections. Pursuant to this mandate, EPA has established maximum contaminant levels (MCLs) for drinking water delivered through public water distribution systems. The maximum contaminant levels of inorganics, organic chemicals, turbidity, and microbiological contaminants are shown in Table 13.2. EPA's primary regulations are mandatory and must be complied with by all public water systems to which they apply. If analysis of the water produced by a water system indicates that an MCL for a contaminant is being exceeded, the system must take steps to stop providing the water to the public or initiate treatment to reduce the contaminant concentration to below the MCL.

EPA has also issued guidelines to the states with regard to secondary drinking-water standards. These appear in Table 13.3. These guidelines apply to drinking water contaminants that may adversely affect the aesthetic qualities of the water (i.e., those qualities that make water appealing and useful), such as odor and appearance. These qualities have no known adverse health effects, and thus secondary regulations are not mandatory. However, most drinking-water systems comply with the limits; they have learned through experience that the odor and appearance of drinking water is not a problem until customers complain. One thing is certain, they will complain.

13.4 WATER QUALITY CHARACTERISTICS OF WATER AND WASTEWATER

In this section, we describe individual pollutants and stressors that affect water quality. Knowledge of the parameters or characteristics most commonly associated with water and wastewater treatment processes is essential to the

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TABLE 13.2
EPA Primary Drinking Water Standards

1. Inorganic Contaminant Levels

Contaminants	Level (mg/L)
Arsenic	0.05
Barium	1.0
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate	10.0
Selenium	0.01
Silver	0.05

2. Organic Contaminant Levels

Chemical	MCL (mg/L)
Chlorinated hydrocarbons	
Endrin	0.0002
Lindane	0.004
Mexthoxychlor	0.1
Toxaphene	0.005
Chlorophenoxys	
2,4-D	0.1
2, 4, 5-TP silvex	0.01

3. Maximum Levels of Turbidity

Reading Basis	MCL Turbidity Units (TUs)
Turbidity reading (monthly average)	1 or up to 5 TUs if the water supplier can demonstrate to the state that the higher turbidity does not interfere with disinfection maintenance of an effective disinfection agent throughout the distribution system, or microbiological determinants
Turbidity reading (based on average of 2 consecutive days)	5 TUs

4. Microbiological Contaminants

		Individual Sample Basis	
Test Method Used	Monthly Basis	Fewer than 20 samples/month	More than 20 samples/month
		Number of Coliform Bacteria Not to Exceed:	
Membrane filter technique	1/100 mL average daily	4/100 mL in more than 1 sample	4/100 mL in more than 5% of samples
Fermentation		Coliform Bacteria Shall Not Be Present in:	
10-mL standard portions	More than 10% of the portions	3 or more portions in more than 1 sample	3 or more portions in more than 5% of samples
100-mL standard portions	More than 60% of the portions	5 portions in more than 1 sample	5 portions in more than 20% of the samples

Source: Adapted from U.S. Environmental Protection Agency, National Interim Primary Drinking Water Regulations, *Federal Register,* Part IV, 1975.

water or wastewater operator. We encourage water and wastewater practitioners to use a holistic approach to managing water quality problems.

It is important to point out that when this text refers to water quality, the definition used is predicated on the intended use of the water. Many parameters have evolved that qualitatively reflect the impact that various contaminants (impurities) have on selected water uses; the following sections provide a brief discussion of these parameters.

13.4.1 Physical Characteristics of Water and Wastewater

The physical characteristics of water and wastewater we are interested in are more germane to the discussion at hand — a category of parameters or characteristics that can be used to describe water quality. One such category is the physical characteristics for water, those that are apparent to the senses of smell, taste, sight, and touch. Solids, turbidity, color, taste and odor, and temperature also fall into this category.

13.4.1.1 Solids

Other than gases, all contaminants of water contribute to the solids content. Classified by their size and state, chemical characteristics, and size distribution, solids can be dispersed in water in both suspended and dissolved forms. In regards to size, solids in water and wastewater can be classified as suspended, settleable, colloidal, or dissolved.

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TABLE 13.3
Secondary Maximum Contaminant Levels

Contaminant	Level	Adverse Effect
Chloride	250 mg/L	Causes taste
Color	15 cu[a]	Appearance problems
Copper	1 mg/L	Tastes and odors
Corrosivity	Noncorrosive	Tastes and odors
Fluoride	2 mg/L	Dental fluorosis
Foaming agents	0.5 mg/L	Appearance problems
Iron	0.3 mg/L	Appearance problems
Manganese	0.05 mg/L	Discolors laundry
Odor	3 TON[b]	Unappealing to drink
pH	6.5–8.5	Corrosion or scaling
Sulfate	250 mg/L	Laxative effect
Total dissolved solids	500 mg/L	Taste, corrosive
Zinc	5 mg/L	Taste, appearance

[a] Cu = color unit
[b] TON = threshold odor number

Source: Adapted from McGhee, T.J., *Water Supply and Sewerage,* McGraw-Hill, New York, p. 161, 1991.

Solids are also characterized as being volatile or nonvolatile. The distribution of solids is determined by computing the percentage of filterable solids by size range. Solids typically include inorganic solids, such as silt, sand, gravel, and clay from riverbanks, and organic matter, such as plant fibers and microorganisms from natural or man-made sources. We use the term siltation to describe the suspension and deposition of small sediment particles in water bodies. In flowing water, many of these contaminants result from the erosive action of water flowing over surfaces.

Sedimentation and siltation can severely alter aquatic communities. Sedimentation may clog and abrade fish gills, suffocate eggs and aquatic insect larvae on the bottom, and fill in the pore space between bottom cobbles where fish lay eggs. Suspended silt and sediment interfere with recreational activities and aesthetic enjoyment at streams and lakes by reducing water clarity and filling in lakes. Sediment may also carry other pollutants into surface waters. Nutrients and toxic chemicals may attach to sediment particles on land and ride the particles into surface waters where the pollutants may settle with the sediment or detach and become soluble in the water column.

Suspended solids are a measure of the weight of relatively insoluble materials in the ambient water. These materials enter the water column as soil particles from land surfaces or sand, silt, and clay from stream bank erosion of channel scour. Suspended solids can include both organic (detritus and biosolids) and inorganic (sand or finer colloids) constituents.

In water, suspended material is objectionable because it provides adsorption sites for biological and chemical agents. These adsorption sites provide attached microorganisms a protective barrier against the chemical action of chlorine. In addition, suspended solids in water may be degraded biologically resulting in objectionable by-products. Thus, the removal of these solids is of great concern in the production of clean, safe drinking water and wastewater effluent.

In water treatment, the most effective means of removing solids from water is by filtration. It should be pointed out, however, that not all solids, such as colloids and other dissolved solids, can be removed by filtration.

In wastewater treatment, suspended solids is an important water-quality parameter and is used to measure the quality of the wastewater influent, monitor performance of several processes, and measure the quality of effluent. Wastewater is normally 99.9% water and 0.1% solids. If a wastewater sample is evaporated, the solids remaining are called total solids. As shown in Table 13.1, EPA has set a maximum suspended-solids standard of 30 mg/L for most treated wastewater discharges.

13.4.1.2 Turbidity

One of the first things that is noticed about water is its clarity. The clarity of water is usually measured by its turbidity. Turbidity is a measure of the extent to which light is either absorbed or scattered by suspended material in water. Both the size and surface characteristics of the suspended material influence absorption and scattering.

Although algal blooms can make waters turbid, in surface water, most turbidity is related to the smaller inorganic components of the suspended solids burden, primarily the clay particles. Microorganisms and vegetable material may also contribute to turbidity. Wastewaters from industry and households usually contain a wide variety of turbidity-producing materials. Detergents, soaps, and various emulsifying agents contribute to turbidity.

In water treatment, turbidity is useful in defining drinking-water quality. In wastewater treatment, turbidity measurements are particularly important whenever ultraviolet radiation (UV) is used in the disinfection process. For UV to be effective in disinfecting wastewater effluent, UV light must be able to penetrate the stream flow. Obviously, stream flow that is turbid works to reduce the effectiveness of irradiation (penetration of light).

The colloidal material associated with turbidity provides absorption sites for microorganisms and chemicals that may be harmful or cause undesirable tastes and odors. Moreover, the adsorptive characteristics of many colloids work to provide protection sites for microorganisms from disinfection processes. Turbidity in running waters interferes with light penetration and photosynthetic reactions.

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TABLE 13.4
Significance of Color in Wastewater

Unit Process	Color	Problem Indicated
Influent of plant	Gray	None
	Red	Blood or other industrial wastes
	Green, yellow, other	Industrial wastes not pretreated (paints, etc.)
	Red or other soil color	Surface runoff into influent, also industrial flows
	Black	Septic conditions or industrial flows

Source: Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

13.4.1.3 Color

Color is another physical characteristic by which the quality of water can be judged. Pure water is colorless. Water takes on color when foreign substances such as organic matter from soils, vegetation, minerals, and aquatic organisms are present. Color can also be contributed to water by municipal and industrial wastes.

Color in water is classified as either true color or apparent color. Water whose color is partly due to dissolved solids that remain after removal of suspended matter is known as true color. Color contributed by suspended matter is said to have apparent color. In water treatment, true color is the most difficult to remove.

Note: Water has an intrinsic color, and this color has a unique origin. Intrinsic color is easy to discern, as can be seen in Crater Lake, OR, which is know for its intense blue color. The appearance of the lake varies from turquoise to deep navy blue depending on whether the sky is hazy or clear. Pure water and ice have a pale blue color.

The obvious problem with colored water is that it is not acceptable to the public. Given a choice, the public prefers clear, uncolored water. Another problem with colored water is the effect it has on laundering, papermaking, manufacturing, textiles, and food processing. The color of water has a profound impact on its marketability for both domestic and industrial use.

In water treatment, color is not usually considered unsafe or unsanitary, but is a treatment problem in regards to exerting a chlorine demand that reduces the effectiveness of chlorine as a disinfectant.

In wastewater treatment, color is not necessarily a problem, but instead is an indicator of the *condition* of the wastewater. Condition refers to the age of the wastewater, which along with odor, provides a qualitative indication of its age. Early in the flow, wastewater is a light brownish-gray color. The color of wastewater containing DO is normally gray. Black-colored wastewater usually accompanied by foul odors, containing little or no DO, is said to be septic. Table 13.4 provides wastewater color information. As the travel time in the collection system increases (flow becomes increasingly more septic), and more anaerobic conditions develop, the color of the wastewater changes from gray to dark gray and ultimately to black.

13.4.1.4 Taste and Odor

Taste and odor are used jointly in the vernacular of water science. The term odor is used in wastewater; taste, obviously, is not a consideration. Domestic sewage should have a musty odor. Bubbling gas and/or foul odor may indicate industrial wastes, anaerobic (septic) conditions, and operational problems. Refer to Table 13.5 for typical wastewater odors, possible problems, and solutions.

In wastewater, odors are of major concern, especially to those who reside in close proximity to a wastewater treatment plant. These odors are generated by gases produced by decomposition of organic matter or by substances added to the wastewater. Because these substances are volatile, they are readily released to the atmosphere at any point where the waste stream is exposed, particularly if there is turbulence at the surface.

Most people would argue that all wastewater is the same; it has a disagreeable odor. It is hard to argue against the disagreeable odor. However, one wastewater operator told us that wastewater "smelled great, smells just like money to me — money in the bank."

This was an operator's view. We also received another opinion of odor problems resulting from wastewater operations. This particular opinion, given by an odor control manager, was quite different. His statement was that "odor control is a never ending problem." He also pointed out that to combat this difficult problem, odors must be contained. In most urban plants, it has become necessary to physically cover all source areas, such as treatment basins, clarifiers, aeration basins, and contact tanks, to prevent odors from leaving the processes. These contained spaces must then be positively vented to wet-chemical scrubbers to prevent the buildup of a toxic concentration of gas.

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TABLE 13.5
Odors in Wastewater Treatment Plant

Odor	Location	Problem	Possible Solution
Earthy, musty	Primary and secondary units	No problem (normal)	None required
Hydrogen sulfide (rotten egg odor)	Influent	Septic	Aerate, chlorinate, oxonizate
	Trickling filters	Septic conditions	More air/less BOD
	Secondary clarifiers	Septic conditions	Remove sludge
	Chlorine contact	Septic conditions	Remove sludge
	General plant	Septic conditions	Good housekeeping
Chlorine like	Chlorine contact tank	Improper chlorine dosage	Adjust chlorine dosage controls
Industrial odors	General plant	Inadequate pretreatment	Enforce sewer use regulations

Source: Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

As mentioned, in drinking water, taste and odor are not normally a problem until the consumer complains. The problem is that most consumers find taste and odor in water aesthetically displeasing. As mentioned, taste and odor do not directly present a health hazard, but they can cause the customer to seek water that tastes and smells good, but may not be safe to drink. Most consumers consider water tasteless and odorless. When consumers find that their drinking water has a taste, odor, or both, they automatically associate the drinking water with contamination.

Water contaminants are attributable to contact with nature or human use. Taste and odor in water are caused by a variety of substances such as minerals, metals, and salts from the soil; constituents of wastewater; and end products produced in biological reactions. When water has a taste but no accompanying odor, the cause is usually inorganic contamination. Water that tastes bitter is usually alkaline, while salty water is commonly the result of metallic salts. However, when water has both taste and odor, the likely cause is organic materials. The list of possible organic contaminants is too long to record here, but petroleum-based products lead the list of offenders. Taste- and odor-producing liquids and gases in water are produced by biological decomposition of organics. A prime example of one of these is hydrogen sulfide; known best for its characteristic rotten-egg taste and odor. Certain species of algae also secrete an oily substance that may produce both taste and odor. When certain substances combine (such as organics and chlorine), the synergistic effect produces taste and odor.

In water treatment, one of the common methods used to remove taste and odor is to oxidize the materials that cause the problem. Oxidants, such as potassium permanganate and chlorine, are used. Another common treatment method is to feed powdered activated carbon before the filter. The activated carbon has numerous small openings that absorb the components that cause the odor and tastes. These contained spaces must then be positively vented to wet-chemical scrubbers to prevent the buildup of toxic concentrations of gas.

13.4.1.5 Temperature

Heat is added to surface and groundwater in many ways. Some of these are natural, and some are artificial. For example, heat is added by natural means to Yellowstone Lake, WY. The Lake, one of the world's largest freshwater lakes, resides in a calderas, situated at more than 7700 ft (the largest high altitude lake in North America). When one attempts to swim in Yellowstone Lake (without a wetsuit), the bitter cold of the water literally takes one's breath away. However, if it were not for the hydrothermal discharges that occur in Yellowstone, the water would be even colder. In regards to human heated water, this most commonly occurs whenever a raw water source is used for cooling water in industrial operations. The influent to industrial facilities is at normal ambient temperature. When it is used to cool machinery and industrial processes and then discharged back to the receiving body, it is often heated.

The problem with heat or temperature increases in surface waters is that it affects the solubility of oxygen in water, the rate of bacterial activity, and the rate at which gases are transferred to and from the water.

Note: It is important to point out that in the examination of water or wastewater, temperature is not normally used to evaluate either. However, temperature is one of the most important parameters in natural surface-water systems. Surface waters are subject to great temperature variations.

Water temperature does partially determine how efficiently certain water treatment processes operate. For example, temperature has an effect on the rate at which chemicals dissolve and react. When water is cold, more chemicals are required for efficient coagulation and flocculation to take place. When water temperature is high, the result may be a higher chlorine demand because of

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the increased reactivity, and there is often an increased level of algae and other organic matter in raw water. Temperature also has a pronounced effect on the solubility of gases in water.

Ambient temperature (temperature of the surrounding atmosphere) has the most profound and universal effect on temperature of shallow natural water systems. When water is used by industry to dissipate process waste heat, the discharge locations into surface waters may experience localized temperature changes that are quite dramatic. Other sources of increased temperatures in running water systems result because of clear-cutting practices in forests (where protective canopies are removed) and from irrigation flows returned to a body of running water.

In wastewater treatment, the temperature of wastewater varies greatly, depending upon the type of operations being conducted at a particular installation. Wastewater is generally warmer than that of the water supply, because of the addition of warm water from industrial activities and households. Wide variation in the wastewater temperature indicates heated or cooled discharges, often of substantial volume. They have any number of sources. For example, decreased temperatures after a snowmelt or rain event may indicate serious infiltration. In the treatment process, temperature not only influences the metabolic activities of the microbial population, but also has a profound effect on such factors as gas-transfer rates and the settling characteristics of the biological solids.

13.4.2 Chemical Characteristics of Water

Another category used to define or describe water quality is its chemical characteristics. The most important chemical characteristics are:

1. Total dissolved solids (TDS)
2. Alkalinity
3. Hardness
4. Fluoride
5. Metals
6. Organics
7. Nutrients

Chemical impurities can be either natural, man-made (industrial), or be deployed in raw water sources by enemy forces.

Some chemical impurities cause water to behave as either an acid or a base. Because either condition has an important bearing on the water treatment process, the pH value must be determined. Generally, the pH influences the corrosiveness of the water, chemical dosages necessary for proper disinfection, and the ability to detect contaminants. The principal contaminants found in water are shown in Table 13.6. These chemical constituents are important because each one affects water use in some manner; each one either restricts or enhances specific uses.

TABLE 13.6
Chemical Constituents Commonly Found in Water

Constituent	
Calcium	Fluorine
Magnesium	Nitrate
Sodium	Silica
Potassium	TDS
Iron	Hardness
Manganese	Color
Bicarbonate	pH
Carbonate	Turbidity
Sulfate	Temperature
Chloride	

Source: Spellman, F.R., *The Science of Water,* Technomic Publ., Lancaster, PA, 1998.

As mentioned, the pH of water is important. As pH rises, for example, the equilibrium (between bicarbonate and carbonate) increasingly favors the formation of carbonate, which often results in the precipitation of carbonate salts. If you have ever had flow in a pipe system interrupted or a heat-transfer problem in your water heater system, then carbonate salts that formed a hard-to-dissolve scale within the system most likely the cause. It should be pointed out that not all carbonate salts have a negative effect on their surroundings. Consider, for example, the case of blue marl lakes; they owe their unusually clear, attractive appearance to carbonate salts.

We mentioned earlier that water has been called the *universal solvent.* This is, of course, a fitting description. The solvent capabilities of water are directly related to its chemical characteristics or parameters.

As mentioned, in water-quality management, total dissolved solids (TDS), alkalinity, hardness, fluorides, metals, organics, and nutrients are the major chemical parameters of concern.

13.4.2.1 Total Dissolved Solids (TDS)

Because of water's solvent properties, minerals dissolved from rocks and soil as water passes over and through it produce TDS (comprised of any minerals, salts, metals, cations or anions dissolved in water). TDS constitutes a part of total solids in water; it is the material remaining in water after filtration.

Dissolved solids may be organic or inorganic. Water may be exposed to these substances within the soil, on surfaces, and in the atmosphere. The organic dissolved constituents of water come from the decay products of

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vegetation, from organic chemicals, and from organic gases.

Dissolved solids can be removed from water by distillation, electrodialysis, reverse osmosis, or ion exchange. It is desirable to remove these dissolved minerals, gases, and organic constituents because they may cause psychological effects and produce aesthetically displeasing color, taste, and odors.

While it is desirable to remove many of these dissolved substances from water, it is not prudent to remove them all. This is the case, for example, because pure, distilled water has a flat taste. Further, water has an equilibrium state with respect to dissolved constituents. If water is out of equilibrium or undersaturated, it will aggressively dissolve materials with which it comes into contact. Because of this problem, substances that are readily dissolvable are sometimes added to pure water to reduce its tendency to dissolve plumbing.

13.4.2.2 Alkalinity

Another important characteristic of water is its alkalinity — a measure of water's ability to neutralize acid or really an expression of buffering capacity. The major chemical constituents of alkalinity in natural water supplies are the bicarbonate, carbonate, and hydroxyl ions. These compounds are mostly the carbonates and bicarbonates of sodium, potassium, magnesium, and calcium. These constituents originate from carbon dioxide (from the atmosphere and as a by-product of microbial decomposition of organic material) and from their mineral origin (primarily from chemical compounds dissolved from rocks and soil).

Highly alkaline waters are unpalatable; this condition has little known significance for human health. The principal problem with alkaline water is the reactions that occur between alkalinity and certain substances in the water. Alkalinity is important for fish and aquatic life because it protects or buffers against rapid pH changes. It is also important because the resultant precipitate can foul water system appurtenances. In addition, alkalinity levels affect the efficiency of certain water treatment processes, especially the coagulation process.

13.4.2.3 Hardness

Hardness is due to the presence of multivalent metal ions that come from minerals dissolved in water. Hardness is based on the ability of these ions to react with soap to form a precipitate or soap scum.

In freshwater, the primary ions are calcium and magnesium; iron and manganese may also contribute. Hardness is classified as carbonate hardness or noncarbonate hardness. Carbonate hardness is equal to alkalinity but a noncarbonate fraction may include nitrates and chlorides. Hardness is either temporary or permanent. Carbonate hardness (temporary hardness) can be removed by boiling. Noncarbonate hardness cannot be removed by boiling and is classified as permanent.

Hardness values are expressed as an equivalent amount or equivalent weight of calcium carbonate (equivalent weight of a substance is its atomic or molecular weight divided by n). Water with a hardness of less than 50 ppm is soft. Above 200 ppm, domestic supplies are usually blended to reduce the hardness value. The U.S. Geological Survey uses the following classification:

Range of Hardness (mg/L [ppm] as $CaCO_3$)	Descriptive Classification
1–50	Soft
51–150	Moderately hard
151–300	Hard
Above 300	Very hard

The impact of hardness can be measured in economic terms. Soap consumption points this out; it represents an economic loss to the water user. When washing with a bar of soap, there is a need to use more soap to get a lather whenever washing in hard water. There is another problem with soap and hardness. When using a bar of soap in hard water, when lather is finally built up, the water has been softened by the soap. The precipitate formed by the hardness and soap (soap curd) adheres to just about anything (tubs, sinks, dishwashers) and may stain clothing, dishes, and other items. There also is a personal problem: the residues of the hardness-soap precipitate may precipitate into the pores, causing skin to feel rough and uncomfortable. Today these problems have been largely reduced by the development of synthetic soaps and detergents that do not react with hardness. However, hardness still leads to other problems, including scaling and laxative effect. Scaling occurs when carbonate hard water is heated and calcium carbonate and magnesium hydroxide are precipitated out of solution, forming a rock-hard scale that clogs hot water pipes and reducing the efficiency of boilers, water heaters, and heat exchangers. Hardness, especially with the presence of magnesium sulfates, can lead to the development of a laxative effect on new consumers.

There are advantages to be gained from usage of hard water. These include:

1. Hard water aids in the growth of teeth and bones.
2. Hard water reduces toxicity to many by poisoning with lead oxide from lead pipelines.
3. Soft waters are suspected to be associated with cardiovascular diseases.[5]

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13.4.2.4 Fluoride

We purposely fluoridate a range of everyday products, notably toothpaste and drinking water, because for decades we have believed that fluoride in small doses has no adverse effects on health to offset its proven benefits in preventing dental decay. The jury is still out on the real benefits of fluoride, even in small amounts.

Fluoride is seldom found in appreciable quantities in surface waters and appears in groundwater in only a few geographical regions. However, fluoride is sometimes found in a few types of igneous or sedimentary rocks. Fluoride is toxic to humans in large quantities and is also toxic to some animals. For example, certain plants used for fodder have the ability to store and concentrate fluoride. When animals consume this forage, they ingest an enormous overdose of fluoride. Animals' teeth become mottled, they lose weight, give less milk, grow spurs on their bones, and become so crippled they must be destroyed.[6]

As mentioned, used in small concentrations (about 1.0 mg/L in drinking water), fluoride can be beneficial. Experience has shown that drinking water containing a proper amount of fluoride can reduce tooth decay by 65% in children between ages 12 to 15.

When large concentrations are used (>2.0 mg/L), discoloration of teeth may result. Adult teeth are not affected by fluoride. EPA sets the upper limits for fluoride based on ambient temperatures because people drink more water in warmer climates; fluoride concentrations should be lower in these areas.

Note: How does fluoridization of a drinking water supply actually work to reduce tooth decay? Fluoride combines chemically with tooth enamel when permanent teeth are forming. The result is teeth that are harder, stronger, and more resistant to decay.

13.4.2.5 Metals

Although iron and manganese are most commonly found in groundwaters, surface waters may also contain significant amounts at times. Metal ions are dissolved in groundwater and surface water when the water is exposed to rock or soil containing the metals, usually in the form of metal salts. Metals can also enter with discharges from sewage treatment plants, industrial plants, and other sources. The metals most often found in the highest concentrations in natural waters are calcium and magnesium. These are usually associated with a carbonate anion and come from the dissolution of limestone rock. As mentioned in the discussion of hardness, the higher the concentration of these metal ions, the harder the water; however, in some waters, other metals can contribute to hardness. Calcium and magnesium are nontoxic and normally absorbed by living organisms more readily than the other metals. Therefore, if the water is hard, the toxicity of a given concentration of a toxic metal is reduced. Conversely, in soft, acidic water, the same concentrations of metals may be more toxic.

In natural water systems, other nontoxic metals are generally found in very small quantities. Most of these metals cause taste problems well before they reach toxic levels.

Fortunately, toxic metals are present in only minute quantities in most natural water systems. Even in small quantities, toxic metals in drinking water are harmful to humans and other organisms. Arsenic, barium, cadmium, chromium, lead, mercury, and silver are toxic metals that may be dissolved in water. Arsenic, cadmium, lead, and mercury, all cumulative toxins, are particularly hazardous. These particular metals are concentrated by the food chain and pose the greatest danger to organisms near the top of the chain.

13.4.2.6 Organics

Organic chemicals in water primarily emanate from synthetic compounds that contain carbon, such as polychlorinated biphenyls, dioxin, and dichlorodiphenyltrichloroethane (all toxic organic chemicals). These synthesized compounds often persist and accumulate in the environment because they do not readily breakdown in natural ecosystems. Many of these compounds can cause cancer in people and birth defects in other predators near the top of the food chain, such as birds and fish.

The presence of organic matter in water is troublesome for the following reasons: "(1) color formation, (2) taste and odor problems, (3) oxygen depletion in streams, (4) interference with water treatment processes, and (5) the formation of halogenated compounds when chlorine is added to disinfect water."[7]

Generally, the source of organic matter in water is from decaying leaves, weeds, and trees; the amount of these materials present in natural waters is usually low. The general category of "organics" in natural waters includes organic matter whose origins could be from both natural sources and from human activites. It is important to distinguish natural organic compounds from organic compounds that are solely man-made (anthropogenic), such as pesticides and other synthetic organic compounds.

Many organic compounds are soluble in water, and surface waters are more prone to contamination by natural organic compounds that are groundwaters. In water, dissolved organics are usually divided into two categories: biodegradable and nonbiodegradeable.

Biodegradable (breakdown) material consists of organics that can be utilized for nutrients (food) by naturally occurring microorganisms within a reasonable length of time. These materials usually consist of alcohols, acids,

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starches, fats, proteins, esters, and aldehydes. They may result from domestic or industrial wastewater discharges, or they may be end products of the initial microbial decomposition of plant or animal tissue. The principle problem associated with biodegradable organics is the effect resulting from the action of microorganisms. Some biodegradable organics can also cause color, taste, and odor problems.

Oxidation and reduction play an important accompanying role in microbial utilization of dissolved organics. In oxidation, oxygen is added or hydrogen is deleted from elements of the organic molecule. Reduction occurs when hydrogen is added to or oxygen is deleted from elements of the organic molecule. The oxidation process is by far more efficient and is predominant when oxygen is available. In oxygen-present (aerobic) environments, the end products of microbial decomposition of organics are stable and acceptable compounds. On the other hand, oxygen-absent (anaerobic) decomposition results in unstable and objectionable end products.

The quantity of oxygen-consuming organics in water is usually determined by measuring the biochemical oxygen demand (BOD). This is the amount of dissolved oxygen needed by aerobic decomposers to break down the organic materials in a given volume of water over a 5-day incubation period at 20ºC (68ºF).

Nonbiodegradeable organics are resistant to biological degradation. For example, constituents of woody plants, such as tannin and lignic acids, phenols, and cellulose, are found in natural water systems and are considered refractory (resistant to biodegradation). In addition, some polysaccharides with exceptionally strong bonds and benzene with its ringed structure are essentially nonbiodegradeable. An example is benzene associated with the refining of petroleum.

Some organics are toxic to organisms and are nonbiodegradeable. These include the organic pesticides and compounds that have combined with chlorine.

Pesticides and herbicides have found widespread use in agriculture, forestry (silviculture), and mosquito control. Surface streams are contaminated via runoff and wash off by rainfall. These toxic substances are harmful to some fish, shellfish, predatory birds, and mammals. Some compounds are toxic to humans.

13.4.2.7 Nutrients

Nutrients (biostimulents) are essential building blocks for healthy aquatic communities, but excess nutrients (especially nitrogen and phosphorous compounds) overstimulate the growth of aquatic weeds and algae. Excessive growth of these organisms can clog navigable waters; interfere with swimming and boating; outcompete native submerged aquatic vegetation; and, with excessive decomposition, lead to oxygen depletion. Oxygen concentrations can fluctuate daily during algae blooms, rising during the day as algae perform photosynthesis and falling at night as algae continue to respire, which consumes oxygen. Beneficial bacteria also consume oxygen as they decompose the abundant organic food supply in dying algae cells.

Plants require large amounts of the nutrients carbon, nitrogen, and phosphorus; otherwise, growth will be limited.

Carbon is readily available from a number of natural sources, including alkalinity, decaying products of organic matter, and dissolved carbon dioxide from the atmosphere. Since carbon is readily available, it is seldom the limiting nutrient. This is an important point because it suggests that identifying and reducing the supply of a particular nutrient can control algal growth. In most cases, nitrogen and phosphorous are essential growth factors and are the limiting factors in aquatic plant growth. Freshwater systems are most often limited by phosphorus.

Nitrogen gas (N_2), which is extremely stable, is the primary component of the earth's atmosphere. Major sources of nitrogen include runoff from animal feedlots, and fertilizer runoff from agricultural fields, municipal wastewater discharges, and certain bacteria and blue-green algae that can obtain nitrogen directly from the atmosphere. In addition, certain forms of acid rain can also contribute nitrogen to surface waters.

Nitrogen in water is commonly found in the form of nitrate (NO_3). Nitrate in drinking water can lead to a serious problem. Specifically, nitrate poisoning in infant humans, including animals, can cause serious problems and even death. Bacteria commonly found in the intestinal tract of infants can convert nitrate to highly toxic nitrites (NO_2). Nitrites can replace oxygen in the bloodstream and result in oxygen starvation that causes a bluish discoloration of the infant ("blue baby" syndrome).

In aquatic environments, phosphorus is found in the form phosphate. Major sources of phosphorus include phosphates in detergents, fertilizer and feedlot runoff, and municipal wastewater discharges.

13.4.3 Chemical Characteristics of Wastewater

The chemical characteristics of wastewater consist of three parts: (1) organic matter, (2) inorganic matter, and (3) gases. Metcalf & Eddy, Inc., point out that in "wastewater of medium strength, about 75% of the suspended solids and 40% of the filterable solids are organic in nature."[8] The organic substances of interest in this discussion include proteins, oil and grease, carbohydrates, and detergents (surfactants).

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13.4.3.1 Organic Substances

Proteins are nitrogenous organic substances of high molecular weight found in the animal kingdom and to a lesser extent in the plant kingdom. The amount present varies from a small percentage found in tomatoes and other watery fruits and in the fatty tissues of meat, to a high percentage in lean meats and beans. All raw foodstuffs, plant and animal, contain proteins. Proteins consist wholly or partially of very large numbers of amino acids. They also contain carbon, hydrogen, oxygen, sulfur, phosphorous, and a fairly high and constant proportion of nitrogen. The molecular weight of proteins is quite high.

Coackley points out that proteinaceous materials constitute a large part of the wastewater biosolids. He also notes that if the biosolids particles do not consist of pure protein, they will be covered with a layer of protein that will govern their chemical and physical behavior.[8] Moreover, the protein content ranges between 15 to 30% of the organic matter present for digested biosolids, and 28 to 50% in the case of activated biosolids. Proteins and urea are the chief sources of nitrogen in wastewater. When proteins are present in large quantities, microorganisms decompose and produce end products that have objectionable foul odors. During this decomposition process, proteins are hydrolyzed to amino acids and then further degraded to ammonia, hydrogen sulfide, and simple organic compounds.

Oils and grease are another major component of foodstuffs. They are also usually related to spills or other releases of petroleum products. Minor oil and grease problems can result from wet weather runoff from highways or the improper disposal in storm drains of motor oil. They are insoluble in water, but dissolve in organic solvents such as petroleum, chloroform, and ether. Fats, oils, waxes, and other related constituents found in wastewater are commonly grouped under the term grease. Fats and oils are contributed in domestic wastewater in butter, lard, margarine, and vegetable fats and oils. Fats, which are compounds of alcohol and glycerol, are among the more stable of organic compounds and are not easily decomposed by bacteria. They can be broken down by mineral acids resulting in the formation of fatty acid and glycerin. When these glycerides of fatty acids are liquid at ordinary temperature they are called oils, and those that are solids are called fats.

The grease content of wastewater can cause many problems in wastewater treatment unit processes. For example, high grease content can cause clogging of filters, nozzles, and sand beds.[10] Moreover, grease can coat the walls of sedimentation tanks and decompose and increase the amount of scum. Additionally, if grease is not removed before discharge of the effluent, it can interfere with the biological processes in the surface waters and create unsightly floating matter and films.[11] In the treatment process, grease can coat trickling filters and interfere with the activated sludge process; this can interfere with the transfer of oxygen from the liquid to the interior of living cells.[12]

Carbohydrates, which are widely distributed in nature and found in wastewater, are organic substances that include starch, cellulose, sugars, and wood fibers; they contain carbon, hydrogen, and oxygen. Sugars are soluble while starches are insoluble in water. The primary function of carbohydrates in higher animals is to serve as a source of energy. In lower organisms (e.g., bacteria), carbohydrates are utilized to synthesize fats and proteins as well as energy. In the absence of oxygen, the end products of decomposition of carbohydrates are organic acids, alcohols, and gases such as carbon dioxide and hydrogen sulfide. The formation of large quantities of organic acids can affect the treatment process by overtaxing the buffering capacity of the wastewater, resulting in a drop in pH and a cessation of biological activity.

Detergents (surfactants) are large organic molecules that are slightly soluble in water and cause foaming in wastewater treatment plants and in the surface waters into which the effluent is discharged. Probably the most serious effect detergents can have on wastewater treatment processes is in their tendency to reduce the oxygen uptake in biological processes. According to Rowe and Abdel-Magid, "detergents affect wastewater treatment processes by (1) lowering the surface, or interfacial, tension of water and increase its ability to wet surfaces with which they come in contact; (2) emulsify grease and oil, deflocculate colloids; (3) induce flotation of solids and give rise to foams; and (4) may kill useful bacteria and other living organisms."[11] Since the development and increasing use of synthetic detergents, many of these problems have been reduced or eliminated.

13.4.3.2 Inorganic Substances

Several inorganic components are common to both wastewater and natural waters and are important in establishing and controlling water quality. Inorganic load in water is the result of discharges of treated and untreated wastewater, various geologic formations, and inorganic substances left in the water after evaporation. Natural waters dissolve rocks and minerals with which they come in contact. As mentioned, many of the inorganic constituents found in natural waters are also found in wastewater. Many of these constituents are added via human use. These inorganic constituents include pH, chlorides, alkalinity, nitrogen, phosphorus, sulfur, toxic inorganic compounds, and heavy metals.

When the pH of a water or wastewater is considered, we are simply referring to the hydrogen ion concentration. Acidity, the concentration of hydrogen ions, drives many chemical reactions in living organisms. A pH value of 7 represents a neutral condition. A low pH value (less than 5)

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indicates acidic conditions; a high pH (greater than 9) indicates alkaline conditions. Many biological processes, such as reproduction, cannot function in acidic or alkaline waters. Acidic conditions also aggravate toxic contamination problems because sediments release toxicants in acidic waters.

Many of the important properties of wastewater are due to the presence of weak acids and bases and their salts. The wastewater treatment process is made up of several different unit processes (these are discussed later). It can be safely stated that one of the most important unit processes in the overall wastewater treatment process is disinfection. pH has an effect on disinfection. This is particularly the case in regards to disinfection using chlorine. For example, with increases in pH, the amount of contact time needed for disinfection using chlorine increases. Common sources of acidity include mine drainage, runoff from mine tailings, and atmospheric deposition.

In the form of the Cl^- ion, chloride is one of the major inorganic constituents in water and wastewater. Sources of chlorides in natural waters are:

1. Leaching of chloride from rocks and soils
2. Coastal areas, salt-water intrusion
3. Agricultural, industrial, domestic, and human wastewater
4. Infiltration of groundwater into sewers adjacent to salt water

The salty taste produced by chloride concentration in potable water is variable and depends on the chemical composition of the water. In wastewater, the chloride concentration is higher than in raw water because sodium chloride (salt) is a common part of the diet and passes unchanged through the digestive system. Because conventional methods of waste treatment do not remove chloride to any significant extent, higher than usual chloride concentrations can be taken as an indication that the body of water is being used for waste disposal.[8]

As mentioned earlier, alkalinity is a measure of the buffering capacity of water, and in wastewater it helps to resist changes in pH caused by the addition of acids. Alkalinity is caused by chemical compounds dissolved from soil and geologic formations and is mainly due to the presence of hydroxyl and bicarbonate ions. These compounds are mostly the carbonates and bicarbonates of calcium, potassium, magnesium, and sodium. Wastewater is usually alkaline. Alkalinity is important in wastewater treatment because anaerobic digestion requires sufficient alkalinity to ensure that the pH will not drop below 6.2; if alkalinity does drop below this level, the methane bacteria cannot function. For the digestion process to operate successfully, the alkalinity must range from about 1000 to 5000 mg/L as calcium carbonate. Alkalinity in wastewater is also important when chemical treatment is used, in biological nutrient removal, and whenever ammonia is removed by air stripping.

In domestic wastewater, "nitrogen compounds result from the biological decomposition of proteins and from urea discharged in body waste."[13] In wastewater treatment, biological treatment cannot proceed unless *nitrogen,* in some form, is present. Nitrogen must be present in the form of organic nitrogen (N), ammonia (NH_3), nitrite (NO_2), or nitrate (NO_3). Organic nitrogen includes such natural constituents as peptides, proteins, urea, nucleic acids, and numerous synthetic organic materials. Ammonia is present naturally in wastewaters. It is produced primarily by deaeration of organic nitrogen-containing compounds and by hydrolysis of area. Nitrite, an intermediate oxidation state of nitrogen, can enter a water system through use as a corrosion inhibitor in industrial applications. Nitrate is derived from the oxidation of ammonia.

Nitrogen data are essential in evaluating the treatability of wastewater by biological processes. If nitrogen is not present in sufficient amounts, it may be necessary to add it to the waste to make it treatable. When the treatment process is complete, it is important to determine how much nitrogen is in the effluent. This is important because the discharge of nitrogen into receiving waters may stimulate algal and aquatic plant growth. These exert a high oxygen demand at nighttime, which adversely affects aquatic life and has a negative impact on the beneficial use of water resources.

Phosphorus (P) is a macronutrient that is necessary to all living cells and is a ubiquitous constituent of wastewater. It is primarily present in the form of phosphates — the salts of phosphoric acid. Municipal wastewaters may contain 10 to 20 mg/L of phosphorus, much of which comes from phosphate builders in detergents. Because of noxious algal blooms that occur in surface waters, there is much interest in controlling the amount of phosphorus compounds that enter surface waters in domestic and industrial waste discharges and natural runoff. This is particularly the case in the U.S. because approximately 15% of the population contributes wastewater effluents to lakes, resulting in eutrophication of these water bodies. Eutrophication leads to significant changes in water quality. Reducing phosphorus inputs to receiving waters can control this problem.

Sulfur (S) is required for the synthesis of proteins and is released in their degradation. The sulfate ion occurs naturally in most water supplies and is also present in wastewater. Sulfate is reduced biologically to sulfide, which in turn can combine with hydrogen to form hydrogen sulfide (H_2S). H_2S is toxic to animals and plants. H_2S in interceptor systems can cause severe corrosion to pipes and appurtenances. In certain concentrations, it is also a deadly toxin.

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Toxic inorganic compounds, such as copper, lead, silver, arsenic, boron, and chromium, are classified as priority pollutants and are toxic to microorganisms. These contaminants must be taken into consideration in the design and operation of a biological treatment process. When introduced into a treatment process, toxic inorganic compounds can kill off the microorganisms needed for treatment and thus stop the treatment process.

Heavy metals are major toxicants found in industrial wastewaters; they may adversely affect the biological treatment of wastewater. Mercury, lead, cadmium, zinc, chromium, and plutonium are among the so-called heavy metals — those with a high atomic mass. (It should be noted that the term, heavy metals, is rather loose and is taken by some to include arsenic, beryllium, and selenium, which are not really metals and are better termed toxic metals.) The presence of any of these metals in excessive quantities will interfere with many beneficial uses of water because of their toxicity. Urban runoff is a major source of lead and zinc in many water bodies. (Note: Lead is a toxic metal that is harmful to human health; there is no safe level for lead exposure. It is estimated that up to 20% of the total lead exposure in children can be attributed to a waterborne route [i.e., consuming contaminated water].) The lead comes from the exhaust of automobiles using leaded gasoline, while zinc comes from tire wear.

13.4.4 Biological Characteristics of Water and Wastewater

Specialists or practitioners who work in the water or wastewater treatment field must not only have a general understanding of the microbiological principles presented in Chapter 11, but also must have some knowledge of the biological characteristics of water and wastewater. This knowledge begins with an understanding that water may serve as a medium in which thousands of biological species spend part, if not all, of their life cycles. It is important to understand that to some extent, all members of the biological community are water-quality parameters. This is because their presence or absence may indicate in general terms the characteristics of a given body of water.

The presence or absence of certain biological organisms is of primary importance to the water or wastewater specialist. These are the pathogens. Pathogens are organisms that are capable of infecting or transmitting diseases in humans and animals. It should be pointed out that these organisms are not native to aquatic systems and usually require an animal host for growth and reproduction. They can, however, be transported by natural water systems. These waterborne pathogens include species of bacteria, viruses, protozoa, and parasitic worms (helminths). In the following sections a brief review of each of these species is provided.

13.4.4.1 Bacteria

The word bacteria (singular: bacterium) comes from the Greek word meaning rod or staff, a shape characteristic of many bacteria. Recall that bacteria are single-celled microscopic organisms that multiply by splitting in two (binary fission). In order to multiply they need carbon dioxide if they are autotrophs, and need organic compounds (dead vegetation, meat, sewage) if they are heterotrophs. Their energy comes either from sunlight if they are photosynthetic or from chemical reaction if they are chemosynthetic. Bacteria are present in air, water, earth, rotting vegetation, and the intestines of animals. Human and animal wastes are the primary source of bacteria in water. These sources of bacterial contamination include runoff from feedlots, pastures, dog runs, and other land areas where animal wastes are deposited. Additional sources include seepage or discharge from septic tanks and sewage treatment facilities. Bacteria from these sources can enter wells that are either open at the land surface or do not have watertight casings or caps. Gastrointestinal disorders are common symptoms of most diseases transmitted by waterborne pathogenic bacteria. In wastewater treatment processes, bacteria are fundamental, especially in the degradation of organic matter that takes place in trickling filters, activated biosolids processes, and biosolids digestion.

13.4.4.2 Viruses

A virus is an entity that carries the information needed for its replication but does not possess the machinery for such replication.[14] They are obligate parasites that require a host in which to live. Viruses are the smallest biological structures known, so they can only be seen with the aid of an electron microscope. Waterborne viral infections are usually indicated by disorders with the nervous system rather than of the gastrointestinal tract. Viruses that are excreted by human beings may become a major health hazard to public health. Waterborne viral pathogens are known to cause poliomyelitis and infectious hepatitis.

Testing for viruses in water is difficult because:

1. They are small.
2. They are of low concentrations in natural waters.
3. There are numerous varieties.
4. They are unstable.
5. There are limited identification methods available.

Because of these testing problems and the uncertainty of viral disinfection, direct recycling of wastewater and the practice of land application of wastewater is a cause of concern.[13]

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13.4.4.3 Protozoa

Protozoa (singular: protozoan) are mobile, single-celled, complete, self-contained organisms that can be free-living or parasitic, pathogenic or nonpathogenic, or microscopic or macroscopic. Protozoa range in size from two to several hundred microns in length. They are highly adaptable and widely distributed in natural waters, although only a few are parasitic. Most protozoa are harmless, only a few cause illness in humans — *Entamoeba histolytica* (amebiasis) and *Giardia lamblia* (giardiasis) being two of the exceptions. Because aquatic protozoa form cysts during adverse environmental conditions, they are difficult to deactivate by disinfection and must undergo filtration to be removed.

13.4.4.4 Worms (Helminths)

Worms are the normal inhabitants in organic mud and organic slime. They have aerobic requirements, but can metabolize solid organic matter not readily degraded by other microorganisms. Water contamination may result from human and animal waste that contains worms. Worms pose hazards primarily to those persons who come into direct contact with untreated water. Swimmers in surface water polluted by sewage or stormwater runoff from cattle feedlots and sewage plant operators are at particular risk.

13.5 CHAPTER REVIEW QUESTIONS AND PROBLEMS

13.1. Those characteristics or range of characteristics that make water appealing and useful are called _____.

13.2. Process by which water vapor is emitted by leaves is known as _____.

13.3. Water we see is known as _____.

13.4. The leading causes of impairment for rivers, lakes, and estuaries are _____.

13.5. All contaminants of water contribute to the _____.

13.6. The clarity of water is usually measured by its _____.

13.7. Water has been called the _____.

13.8. A measure of water's ability to neutralize acid is known as _____.

13.9. A pH value of 7 represents a _____.

13.10. There is no safe level for _____ exposure.

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14 Biomonitoring, Monitoring, Sampling, and Testing

In January, we take our nets to a no-name stream in the foothills of the Blue Ridge Mountains of Virginia to do a special kind of macroinvertebrate monitoring — looking for "winter stoneflies." Winter stoneflies have an unusual life cycle. Soon after hatching in early spring, the larvae bury themselves in the streambed. They spend the summer lying dormant in the mud, thereby avoiding problems like overheated streams, low oxygen concentrations, fluctuating flows, and heavy predation. In later November, they emerge, grow quickly for a couple of months, and then lay their eggs in January.

January monitoring of winter stoneflies helps in interpreting the results of spring and fall macroinvertebrate surveys. In spring and fall, a thorough benthic survey is conducted, based on *Protocol II* of the USEPA's *Rapid Bioassessment Protocols for Use in Streams and Rivers*. Some sites on various rural streams have poor diversity and sensitive families. Is the lack of macroinvertebrate diversity because of specific warm-weather conditions, high water temperature, low oxygen, or fluctuating flows, or is some toxic contamination present? In the January screening, if winter stoneflies are plentiful, seasonal conditions were probably to blame for the earlier results; if winter stoneflies are absent, the site probably suffers from toxic contamination (based on our rural location, probably emanating from non-point sources) that is present year-round.

Though different genera of winter stoneflies are found in our region (southwestern Virginia), Allocapnia is sought because it is present even in the smallest streams.[1]

14.1 WHAT IS BIOMONITORING?

The life in, and physical characteristics of, a stream ecosystem provide insight into the historical and current status of its quality. The assessment of a water body ecosystem based on organisms living in it is called biomonitoring. The assessment of the system based on its physical characteristics is called a habitat assessment. Biomonitoring and habitat assessments are tools used by stream ecologists to assess the water quality of a stream.

Biological monitoring involves the use or the observation of organisms to assess environmental condition. Biological observation is more representative as it reveals cumulative effects as opposed to chemical observation, which is representative only at the actual time of sampling. The presence of benthic macroinvertebrates is monitored; as mentioned, these are the larger organisms, such as aquatic insects, insect larvae, and crustaceans, that live in the bottom portions of a waterway for part their life cycle. Routine surveys of macroinvertebrates of lakes, wetlands, rivers, and streams are done in order to measure the biohealth, or biodiversity, of the resource surveyed. They are ideal for use in biomonitoring, as they are ubiquitous, relatively sedentary, and long-lived. They provide a cross-section of the situation, as some species are extremely sensitive to pollution, while others are more tolerant. However, like toxicity testing, biomonitoring does not tell you why animals are present or absent.

As mentioned, benthic macroinvertebrates are excellent indicators of stream conditions. This is the case for several reasons:

1. Biological communities reflect overall ecological integrity (i.e., chemical, physical, and biological integrity). Therefore, biosurvey results directly assess the status of a waterbody relative to the primary goal of the Clean Water Act (CWA).
2. Biological communities integrate the effects of different stressors, providing a broad measure of their aggregate impact.
3. Because they are ubiquitous, communities integrate the stressors over time and provide an ecological measure of fluctuating environmental conditions.
4. Routine monitoring of biological communities can be relatively inexpensive because they are easy to collect and identify.
5. The status of biological communities is of direct interest to the public as a measure of a particular environment.
6. Where criteria for specific ambient impacts do not exist (e.g., nonpoint-sources that degrade habitats), biological communities may be the only practical means of evaluation.[2]

Benthic macroinvertebrates have an advantage over other monitoring methods. They act as continuous monitors of the water they live in. Unlike chemical monitoring, which provides information about water quality at the time of measurement (a snapshot), biological monitoring can

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provide information about past or episodic pollution (a continuous videotape). This concept is analogous to miners who took canaries into deep mines with them to test for air quality. If the canary died, the miners knew the air was bad and they had to leave the mine. Biomonitoring a water body ecosystem uses the same theoretical approach. Aquatic macroinvertebrates are subject to pollutants in the water body. Consequently, the health of the organisms reflects the quality of the water they live in. If the pollution levels reach a critical concentration, certain organisms will migrate away, fail to reproduce, or die, eventually leading to the disappearance of those species at the polluted site. Normally, these organisms will return if conditions improve in the system.[3]

When are biomonitoring surveys conducted? Biomonitoring (and the related term, bioassessment) surveys are conducted before and after an anticipated impact to determine the effect of the activity on the water body habitat. Surveys are also performed periodically to monitor water body habitats and watch for unanticipated impacts. Finally, biomonitoring surveys are designed to reference conditions or to set biocriteria (serve as monitoring thresholds to signal future impacts, regulatory actions, etc.) for determining that an impact has occurred.[4]

Note: The primary justification for bioassessment and monitoring is that degradation of water body habitats affects the biota using those habitats. Therefore, the living organisms provide the most direct means of assessing real environmental impacts.

14.1.1 Biotic Indices (Streams)

Certain common aquatic organisms, by indicating the extent of oxygenation of a stream, may be regarded as indicators of the intensity of pollution from organic waste. The responses of aquatic organisms in waterways to large quantities of organic wastes are well documented. They occur in a predictable cyclical manner. For example, upstream from the discharge point, a stream can support a wide variety of algae, fish, and other organisms. However, in the section of the water body where oxygen levels are low (below 5 ppm), only a few types of worms survive. As stream flow courses downstream, oxygen levels recover, and those species that can tolerate low rates of oxygen (such as gar, catfish, and carp) begin to appear. In a stream, eventually, at some further point downstream, a clean water zone reestablishes itself and a more diverse and desirable community of organisms returns.

During this characteristic pattern of alternating levels of dissolved oxygen (DO) (in response to the dumping of large amounts of biodegradable organic material), a stream goes through a cycle called an oxygen sag curve. Its state can be determined using the biotic index as an indicator of oxygen content.

The biotic index is a systematic survey of macroinvertebrates organisms. Macroinvertebrates can be very descriptive of the overall water quality of a waterway, but they cannot pinpoint specific chemical parameters. Because the diversity of species in a stream is often a good indicator of the presence of pollution, the biotic index can be used to correlate with stream quality. Observation of types of species present or missing is used as an indicator of stream pollution. The biotic index, used in the determination of the types, species, and numbers of biological organisms present in a stream, is commonly used as an auxiliary to biochemical oxygen demand (BOD) determination in determining stream pollution.

The biotic index is based on two principles:

1. A large dumping of organic waste into a stream tends to restrict the variety of organisms at a certain point in the stream.
2. As the degree of pollution in a stream increases, key organisms tend to disappear in a predictable order. The disappearance of particular organisms tends to indicate the water quality of the stream.

There are several different forms of the biotic index. In Great Britain, for example, the Trent Biotic Index, the Chandler score, the Biological Monitoring Working Party (BMWP) score, and the Lincoln Quality Index are widely used. Most of the forms use a biotic index that ranges from 0 to 10. The most polluted stream, which contains the smallest variety of organisms, is at the lowest end of the scale (0); the clean streams are at the highest end (10). A stream with a biotic index of greater than 5 will support game fish; on the other hand, a stream with a biotic index of less than 4 will not support game fish.

As mentioned, because they are easy to sample, macroinvertebrates have predominated in biological monitoring. In addition, macroinvertebrates can be easily identified using identification keys that are portable and easily used in field settings. Present knowledge of macroinvertebrate tolerances and response to stream pollution is well documented. In the U.S., for example, the Environmental Protection Agency (EPA) has required states to incorporate a narrative biological criteria into its water quality standards by 1993. The National Park Service (NPS) has collected macroinvertebrate samples from American streams since 1984. Through their sampling effort, NPS has been able to derive quantitative biological standards.[5]

Macroinvertebrates are a diverse group. They demonstrate tolerances that vary between species. Discrete differences tend to show up, containing both tolerant and sensitive indicators.

The biotic index provides a valuable measure of pollution. This is especially the case for species that are very sensitive to lack of oxygen. An example of an organism that is commonly used in biological monitoring is the

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TABLE 14.1
BMWP Score System

Families	Common-Name Examples	Score
Heptageniidae	Mayflies	10
Leuctridae	Stoneflies	
Aeshnidae	Dragonflies	8
Polycentropidae	Caddisflies	7
Hydrometridae	Water Strider	
Gyrinidae	Whirligig beetle	5
Chironomidae	Mosquitoes	2
Oligochaeta	Worms	1

Note: Modified for illustrative purposes.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

stonefly. Stonefly larvae live underwater and survive best in well-aerated, unpolluted waters with clean gravel bottoms. When stream water quality deteriorates due to organic pollution, stonefly larvae cannot survive. The degradation of stonefly larvae has an exponential effect upon other insects and fish that feed off the larvae; when the stonefly larvae disappears, so do many insects and fish.[6]

Table 14.1 shows a modified version of the BMWP biotic index. Considering that the BMWP biotic index indicates ideal stream conditions, it takes into account that the sensitivities of different macroinvertebrate species are represented by diverse populations and are excellent indicators of pollution. These aquatic macroinvertebrates are organisms that are large enough to be seen by the unaided eye. Moreover, most aquatic macroinvertebrates species live for at least a year, and they are sensitive to stream water quality both on a short-term and long-term basis. For example, mayflies, stoneflies, and caddisflies are aquatic macroinvertebrates that are considered clean-water organisms. They are generally the first to disappear from a stream if water quality declines and are given a high score. On the other hand, tubificid worms (which are tolerant to pollution) are given a low score.

In Table 14.1, a score of 1 to 10 is given for each family present. A site score is calculated by adding the individual family scores. The site score or total score is then divided by the number of families recorded to derive the average score per taxon (ASPT). High ASPT scores result due to such taxa as stoneflies, mayflies, and caddisflies being present in the stream. A low ASPT score is obtained from streams that are heavily polluted and dominated by tubificid worms and other pollution-tolerant organisms.

From Table 14.1, it can be seen that those organisms having high scores, especially mayflies and stoneflies, are the most sensitive. Other organisms, such as dragonflies and caddisflies, are very sensitive to any pollution (deoxy-

TABLE 14.2
Sample Index of Macroinvertebrates

Group One (Sensitive)	Group Two (Somewhat Sensitive)	Group Three (Tolerant)
Stonefly larva	Alderfly larva	Aquatic worm
Caddisfly larva	Damselfly larva	Midgefly larva
Water penny larva	Cranefly larva	Blackfly larva
Riffle beetle adult	Beetle adult	Leech
Mayfly larva	Dragonfly larva	Snails
Gilled snail	Sowbugs	

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.1.1.1 Benthic Macroinvertebrate Biotic Index

The benthic macroinvertebrate biotic index employs the use of certain benthic macroinvertebrates to determine (gauge) the water quality (relative health) of a water body (stream or river).

In this discussion, benthic macroinvertebrates are classified into three groups based on their sensitivity to pollution. The number of taxa in each of these groups is tallied and assigned a score. The scores are then summed to yield a score that can be used as an estimate of the quality of the water body life.

14.1.1.1.1 Metrics within the Benthic Macroinvertebrates

The three groups based on the sensitivity to pollution are described as follows:

Group One — Indicators of poor water quality
Group Two — Indicators of moderate water quality
Group Three — Indicators of good water quality

A sample index of macroinvertebrates, concerning the subject of sensitivity to pollution, is listed in Table 14.2.

In summary, it can be said that unpolluted streams normally support a wide variety of macroinvertebrates and other aquatic organisms with relatively few of any one kind. Any significant change in the normal population usually indicates pollution.

14.2 BIOLOGICAL SAMPLING (STREAMS)

A few years ago, we were preparing to perform benthic macroinvertebrate sampling protocols in a wadable section in one of the countless reaches of the Yellowstone River, WY. It was autumn, windy, and cold. Before we stepped into the slow-moving frigid waters, we stood for a moment at the bank and took in the surroundings.

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The pallet of autumn is austere in Yellowstone. The coniferous forests east of the Mississippi lack the bronzes, coppers, peach-tinted yellows, and livid scarlets that set the mixed stands of the East aflame. All we could see in that line was the quaking aspen and its gold.

This autumnal gold, which provides the closest thing to eastern autumn in the West, is mined from the narrow, rounded crowns of *Populus tremuloides*. The aspen trunks stand stark white and antithetical against the darkness of the firs and pines; the shiny pale gold leaves sensitive to the slightest rumor of wind. Agitated by the slightest hint of breeze, the gleaming upper surfaces bounced the sun into our eyes. Each tree scintillated, like a show of gold coins in free fall. The aspens' bright, metallic flash seemed, in all their glittering motion, to make a valiant dying attempt to fill the spectrum of fall.

As bright and glorious as they are, we did not care that they could not approach the colors of an eastern autumn. While nothing is comparable to experiencing leaf-fall in autumn along the Appalachian Trail, the fact that this autumn was not the same simply did not matter. This spirited display of gold against dark green lightened our hearts and eased the task that was before us, warming the thought of the bone-chilling water and all. With the aspens' gleaming gold against the pines and firs, it simply did not seem to matter.

Notwithstanding the glories of nature alluded to above, one should not be deceived. Conducting biological sampling in a water body is not only the nuts and bolts of biological sampling, but it is also very hard and important work.

14.2.1 Biological Sampling: Planning

When planning a biological sampling outing, it is important to determine the precise objectives. One important consideration is to determine whether sampling will be accomplished at a single point or at isolated points. Additionally, frequency of sampling must be determined. That is, will sampling be accomplished at hourly, daily, weekly, monthly, or even longer intervals? Whatever sampling frequency is chosen, the entire process will probably continue over a protracted period (i.e., preparing for biological sampling in the field might take several months from the initial planning stages to the time when actual sampling occurs). An experienced freshwater ecologist should be centrally involved in all aspects of planning.

The EPA, in its *Monitoring Water Quality: Intensive Stream Bioassay*,[7] points out that the following issues should be considered in planning the sampling program:

1. Availability of reference conditions for the chosen area
2. Appropriate dates to sample in each season
3. Appropriate sampling gear
4. Availability of laboratory facilities
5. Sample storage
6. Data management
7. Appropriate taxonomic keys, metrics, or measurement for macroinvertebrate analysis
8. Habitat assessment consistency
9. A U.S. Geological Survey (USGS) topographical map
10. Familiarity with safety procedures

Once the initial objectives (issues) have been determined and the plan devised, then the sampler can move to other important aspects of the sampling procedure. Along with the items just mentioned, it is imperative that the sampler understands what biological sampling is all about.

Biological sampling allows for rapid and general water quality classification. Rapid classification is possible because quick and easy cross-checking between stream biota and a standard stream biotic index is possible. Biological sampling is typically used for general water quality classification in the field because sophisticated laboratory apparatus is usually not available. Additionally, stream communities often show a great deal of variation in basic water quality parameters such as DO, BOD, suspended solids, and coliform bacteria. This occurrence can be observed in eutrophic lakes that may vary from oxygen saturation to less than 0.5 mg/L in a single day, and the concentration of suspended solids may double immediately after a heavy rain. The sampling method chosen must also take into account the differences in the habits and habitats of the aquatic organisms. Tchobanoglous and Schroeder explain, "Sampling is one of the most basic and important aspects of water quality management."[8]

The first step toward ensuring accurate measurement of a stream's water quality is to make sure that the intended sampling targets are the most likely to provide the information that is being sought. Second, it is essential that representative samples be collected. Laboratory analysis is meaningless if the sample collected is not representative of the aquatic environment being analyzed. As a rule, samples should be taken at many locations, as often as possible. If, for example, you are studying the effects of sewage discharge into a stream, you should first take at least six samples upstream of the discharge, six samples at the discharge, and at least six samples at several points below the discharge for 2 to 3 days (the six-six-six sampling rule). If these samples show wide variability, then the number of samples should be increased. On the other hand, if the initial samples exhibit little variation, then a reduction in the number of samples may be appropriate.[9]

When planning the biological sampling protocol (using biotic indices as the standards) remember that when the sampling is to be conducted in a stream, findings are based on the presence or absence of certain organisms. The absence of these organisms must be a function of

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pollution and not of some other ecological problem. The preferred (favored in this text) aquatic group for biological monitoring in stream is the macroinvertebrates, which are usually retained by 30 mesh sieves (pond nets).

14.2.2 Sampling Stations

After determining the number of samples to be taken, sampling stations (locations) must be determined. Several factors determine where the sampling stations should be set up. These factors include: stream habitat types, the position of the wastewater effluent outfalls, stream characteristics, stream developments (dams, bridges, navigation locks, and other man-made structures), the self-purification characteristics of the stream, and the nature of the objectives of the study.[10]

The stream habitat types used in this discussion are those that are macroinvertebrate assemblage in stream ecosystems. Some combination of these habitats would be sampled in a multihabitat approach to benthic sampling:[11]

1. Cobble (hard substrate) — Cobble is prevalent in the riffles (and runs), which are a common feature throughout most mountain and piedmont streams. In many high-gradient streams, this habitat type will be dominant. However, riffles are not a common feature of most coastal or other low-gradient streams. Sample shallow areas with coarse substrates (mixed gravel, cobble or larger) by holding the bottom of the dip net against the substrate and dislodging organisms by kicking (this is where the designated kicker, a sampling partner, comes in handy) the substrate for 0.5 m upstream of the net.
2. Snags — Snags and other woody debris that have been submerged for a relatively long period (not recent deadfall) provide excellent colonization habitat. Sample submerged woody debris by jabbing in medium-sized snag material (sticks and branches). The snag habitat may be kicked first to help to dislodge organisms, but only after placing the net downstream of the snag. Accumulated woody material in pool areas is considered snag habitat. Large logs should be avoided because they are generally difficult to sample adequately.
3. Vegetated banks — When lower banks are submerged and have roots and emergent plants associated with them, they are sampled in a fashion similar to snags. Submerged areas of undercut banks are good habitats to sample. Sample banks with protruding roots and plants by jabbing into the habitat. Bank habitat can be kicked first to help dislodge organisms, but only after placing the net downstream.
4. Submerged macrophytes — Submerged macrophytes are seasonal in their occurrence and may not be a common feature of many streams, particularly those that are high gradient. Sample aquatic plants that are rooted on the bottom of the stream in deep water by drawing the net through the vegetation from the bottom to the surface of the water (maximum of 0.5 m each jab). In shallow water, sample by bumping or jabbing the net along the bottom in the rooted area, avoiding sediments where possible.
5. Sand (and other fine sediment) — Usually the least productive macroinvertebrate habitat in streams, this habitat may be the most prevalent in some streams. Sample banks of unvegetated or soft soil by bumping the net along the surface of the substrate rather than dragging the net through soft substrate; this reduces the amount of debris in the sample.

It is usually impossible to go out and count each and every macroinvertebrate present in a waterway. This would be comparable to counting different sizes of grains of sand on the beach. Thus, in a biological sampling program (i.e., based on our experience), the most common sampling methods are the transect and the grid. Transect sampling involves taking samples along a straight line either at uniform or at random intervals (see Figure 14.1). The transect involves the cross section of a lake or stream or the longitudinal section of a river or stream. The transect sampling method allows for a more complete analysis by including variations in habitat.

In grid sampling, an imaginary grid system is placed over the study area. The grids may be numbered, and random numbers are generated to determine which grids should be sampled (see Figure 14.2). This type of sampling method allows for quantitative analysis because the grids are all of a certain size. For example, to sample a stream for benthic macroinvertebrates, grids that are 0.25 m^2 may be used. The weight or number of benthic macroinvertebrates per square meter can then be determined.

Random sampling requires that each possible sampling location have an equal chance of being selected. Numbering all sampling locations, and then using a computer, calculator, or a random numbers table to collect a series of random numbers can accomplish this. An illustration of how to put the random numbers to work is provided in the following example. Given a pond that has 300 grid units, find 8 random sampling locations using the following sequence of random numbers taken from a standard random numbers table: 101, 209, 007, 018, 099, 100, 017, 069, 096, 033, 041, 011. The first eight numbers of the sequence could be selected and only grids would be sampled to obtain a random sample.

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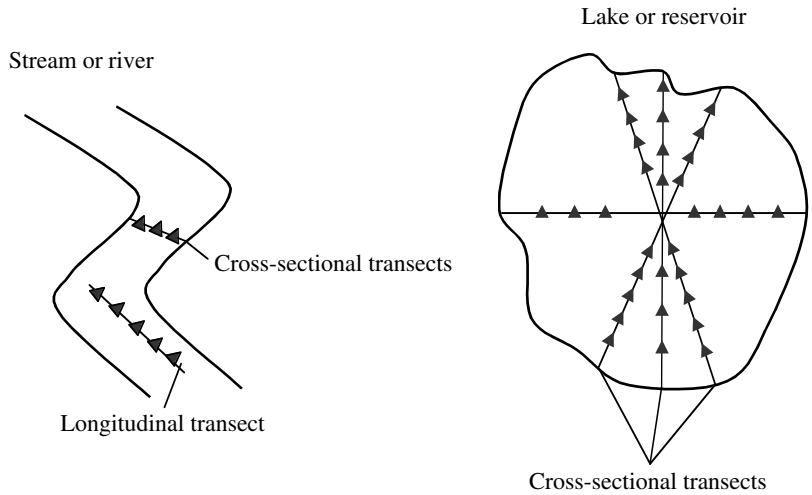

FIGURE 14.1 Transect sampling. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

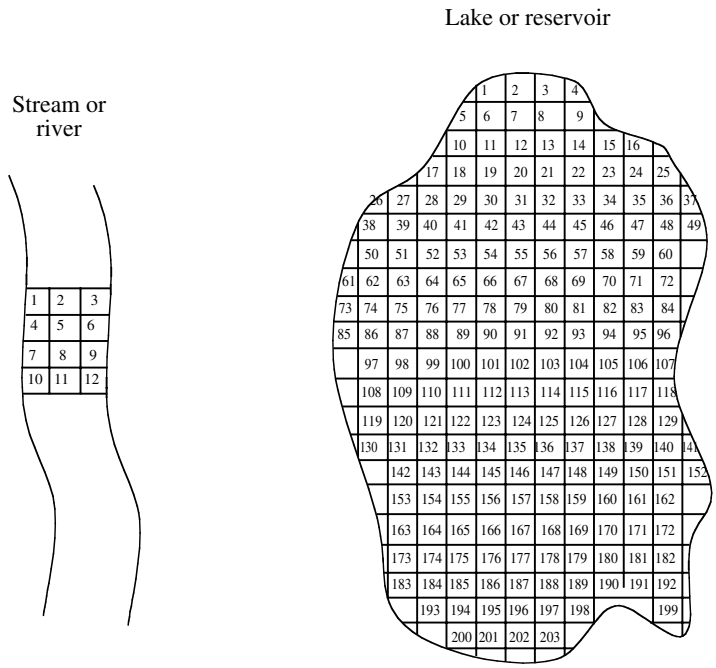

FIGURE 14.2 Grid sampling. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.2.3 Sample Collection

(Note: The following procedures are suggested by EPA in *Volunteer Stream Monitoring: A Methods Manual*, Washington, D.C., Aug. 18, 2000, pp. 1–35.)

After establishing the sampling methodology and the sampling locations, the frequency of sampling must be determined. The more samples collected, the more reliable the data will be. A frequency of once a week or once a month will be adequate for most aquatic studies. Usually, the sampling period covers an entire year so that yearly variations may be included. The details of sample collection will depend on the type of problem that is being solved and will vary with each study. When a sample is collected, it must be carefully identified with the following information:

1. Location — Name of water body and place of study and longitude and latitude.
2. Date and time.
3. Site — Point of sampling (sampling location).
4. Name of collector.

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5. Weather — Temperature, precipitation, humidity, wind, etc.
6. Miscellaneous — Any other important information (e.g., observations).
7. Field notebook — On each sampling day, notes on field conditions should be written. For example, miscellaneous notes and weather conditions can be entered. Additionally, notes that describe the condition of the water are also helpful (color, turbidity, odor, algae, etc.). All unusual findings and condition should also be entered.

14.2.3.1 Macroinvertebrate Sampling Equipment

In addition to the appropriate and applicable sampling equipment described in Section 14.2.5, assemble the following equipment.

1. Jars (two, at least quart size), plastic, wide-mouth with tight cap (one should be empty and the other filled about 2/3 with 70% ethyl alcohol)
2. Hand lens, magnifying glass, or field microscope
3. Fine-point forceps.
4. Heavy-duty rubber gloves
5. Plastic sugar scoop or ice-cream scoop
6. Kink net (rocky-bottom stream) or dip net (muddy-bottom stream)
7. Buckets (two; see Figure 14.3)
8. String or twine (50 yards) and tape measure
9. Stakes (four)
10. Orange (a stick, an apple, or a fish float may also be used in place of an orange) to measure velocity
11. Reference maps indicating general information pertinent to the sampling area, including the surrounding roadways, as well as a hand-drawn station map
12. Station ID tags
13. Spray water bottle
14. Pencils (at least 2)

14.2.3.2 Macroinvertebrate Sampling: Rocky-Bottom Streams

Rocky-bottom streams are defined as those with bottoms made up of gravel, cobbles, and boulders in any combination. They usually have definite riffle areas. As mentioned, riffle areas are fairly well oxygenated and, therefore, are prime habitats for benthic macroinvertebrates. In these streams, we use the rocky-bottom sampling method described below.

14.2.3.2.1 Rocky-Bottom Sampling Method

The following method of macroinvertebrate sampling is used in streams that have riffles and gravel or cobble substrates. Three samples are to be collected at each site, and a composite sample is obtained (i.e., one large total sample).

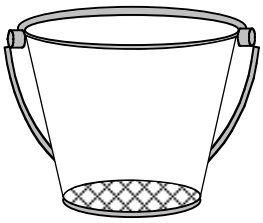

FIGURE 14.3 Sieve bucket. Most professional biological monitoring programs employ sieve buckets as holding containers for composited samples. These buckets have a mesh bottom that allows water to drain out while the organisms and debris remain. This material can then be easily transferred to the alcohol-filled jars. However, sieve buckets can be expensive. Many volunteer programs employ alternative equipment, such as the two regular buckets described in this section. Regardless of the equipment, the process for compositing and transferring the sample is basically the same. The decision is one of cost and convenience. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Step 1 — A site should have already been located on a map, with its latitude and longitude indicated.

1. Samples will be taken in 3 different spots within a 100-yd stream site. These spots may be three separate riffles; one large riffle with different current velocities; or, if no riffles are present, three run areas with gravel or cobble substrate. Combinations are also possible (e.g., site has only one small riffle and several run areas). Mark off the 100-yd stream site. If possible, it should begin at least 50 yd upstream of any man-made modification of the channel, such as a bridge, dam, or pipeline crossing. Avoid walking in the stream because this might dislodge macroinvertebrates and disturb later sampling results.
2. Sketch the 100-yd sampling area. Indicate the location of the three sampling spots on the sketch. Mark the most downstream site as Site 1, the middle site as Site 2, and the upstream site as Site3.

Step 2 — Get into place.

1. Always approach sampling locations from the downstream end and sample the site furthest downstream first (Site 1). This prevents biasing of the second and third collections with dislodged sediment of macroinvertebrates. Always use a clean kick-seine, relatively free of mud and debris from previous uses. Fill a bucket about one-third full with stream water, and fill your spray bottle.

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2. Select a 3 × 3-ft riffle area for sampling at Site 1. One member of the team, the net holder, should position the net at the downstream end of this sampling area. Hold the net handles at a 45-degree angle to the water's surface. Be sure that the bottom of the net fits tightly against the streambed so that no macroinvertebrates escape under the net. You may use rocks from the sampling area to anchor the net against the stream bottom. Do not allow any water to flow over the net.

Step 3 — Dislodge the macroinvertebrates.

1. Pick up any large rocks in the 3 × 3-ft sampling area and rub them thoroughly over the partially filled bucket so that any macroinvertebrates clinging to the rocks will be dislodged into the bucket. Then place each cleaned rock outside of the sampling area. After sampling is completed, rocks can be returned to the stretch of stream they came from.
2. The member of the team designated as the kicker should thoroughly stir up the sampling areas with their feet, starting at the upstream edge of the 3 × 3-ft sampling area and working downstream, moving toward the net. All dislodged organisms will be carried by the stream flow into the net. Be sure to disturb the first few inches of stream sediment to dislodge burrowing organisms. As a guide, disturb the sampling area for about 3 min, or until the area is thoroughly worked over.
3. Any large rocks used to anchor the net should be thoroughly rubbed into the bucket as above.

Step 4 — Remove the net.

1. Remove the net without allowing any of the organisms it contains to wash away. While the net holder grabs the top of the net handles, the kicker grabs the bottom of the net handles and the net's bottom edge. Remove the net from the stream with a forward scooping motion.
2. Roll the kick net into a cylinder shape and place it vertically in the partially filled bucket. Pour or spray water down the net to flush its contents into the bucket. If necessary, pick debris and organisms from the net by hand. Release any caught fish, amphibians, or reptiles back into the stream.

Step 5 — Collect the second and third samples.

1. Once all of the organisms have been removed from the net, repeat the steps above at Sites 2 and 3. Put the samples from all three sites into the same bucket. Combining the debris and organisms from all three sites into the same bucket is called compositing.

Note: If your bucket is nearly full of water after you have washed the net clean, let the debris and organisms settle to the bottom. Cup the net over the bucket and pour the water through the net into a second bucket. Inspect the water in the second bucket to be sure there are no organisms.

Step 6 — Preserve the sample.

1. After collecting and compositing all three samples, it is time to preserve the sample. All team members should leave the stream and return to a relatively flat section of the stream bank with their equipment. The next step will be to remove large pieces of debris (leaves, twigs, and rocks) from the sample. Carefully remove the debris one piece at a time. While holding the material over the bucket, use the forceps, spray bottle, and your hands to pick, rub, and rinse the leaves, twigs, and rocks to remove any attached organisms. Use a magnifying lens and forceps to find and remove small organisms clinging to the debris. When satisfied that the material is clean, discard it back into the stream.
2. The water will have to be drained before transferring material to the jar. This process will require two team members. Place the kick net over the second bucket, which has not yet been used and should be completely empty. One team member should push the center of the net into bucket #2, creating a small indentation or depression. Hold the sides of the net closely over the mouth of the bucket. The second person can now carefully pour the remaining contents of bucket #1 onto a small area of the net to drain the water and concentrate the organisms. Use care when pouring so that organisms are not lost over the side of the net (see Figure 14.4).

   Use the spray bottle, forceps, sugar scoop, and gloved hands to remove all material from bucket #1 onto the net. When you are

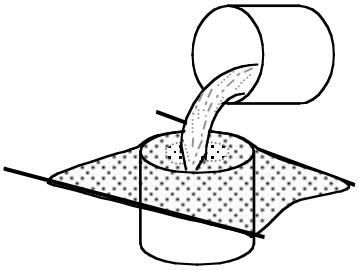

FIGURE 14.4 Pouring sample water through the net. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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satisfied that bucket #1 is empty, use your hands and the sugar scoop to transfer the material from the net into the empty jar.

Bucket #2 captures the water and any organisms that might have fallen through the netting during pouring. As a final check, repeat the process above, but this time, pour bucket #2 over the net, into bucket #1. Transfer any organisms on the net into the jar.

3. Fill the jar (so that all material is submerged) with the alcohol from the second jar. Put the lid tightly back onto the jar, and gently turn the jar upside down two or three times to distribute the alcohol and remove air bubbles.
4. Complete the sampling station ID tag. Be sure to use a pencil, since a pen's ink will run in the alcohol. The tag includes your station number, the stream, and location (e.g., upstream from a road crossing), date, time, and the names of the members of the collecting team. Place the ID tag into the sample container, written side facing out, so that identification can be seen clearly.

14.2.3.2.2 Rocky-Bottom Habitat Assessment

The habitat assessment (including measuring general characteristics and local land use) for a rocky-bottom stream is conducted in a 100-yd section of stream that includes the riffles from which organisms were collected.

Step 1 — Delineate the habitat assessment boundaries.

1. Begin by identifying the most downstream riffle that was sampled for macroinvertebrates. Using tape measure or twine, mark off a 100-yd section extending 25 yd below the downstream riffle and about 75 yd upstream.
2. Complete the identifying information of the field data sheet for the habitat assessment site. On the stream sketch, be as detailed as possible, and be sure to note which riffles were sampled.

Step 2 — Describe the general characteristics and local land use on the field sheet.

1. For safety reasons as well as to protect the stream habitat, it is best to estimate the following characteristics rather than actually wade into the stream to measure them:
   A. Water appearance can be a physical indicator of water pollution:
      1. Clear — Colorless, transparent
      2. Milky — Cloudy-white or gray, not transparent; might be natural or due to pollution
      3. Foamy — might be natural or due to pollution, generally detergents or nutrients (foam that is several inches high and does not brush apart easily is generally due to pollution)
      4. Turbid — Cloudy brown due to suspended silt or organic material
      5. Dark brown — might indicate that acids are being released into the stream due to decaying plants
      6. Oily sheen — Multicolored reflection might indicate oil floating in the stream, although some sheens are natural
      7. Orange — Might indicate acid drainage
      8. Green — Might indicate that excess nutrients are being released into the stream
   B. Water odor can be a physical indicator of water pollution:
      1. None or natural smell
      2. Sewage — Might indicate the release of human waste material
      3. Chlorine — Might indicate that a sewage treatment plant is over-chlorinating its effluent
      4. Fishy — Might indicate the presence of excessive algal growth or dead fish
      5. Rotten eggs — Might indicate sewage pollution (the presence of a natural gas)
   C. Water temperature can be particularly important for determining whether the stream is suitable as habitat for some species of fish and macroinvertebrates that have distinct temperature requirements. Temperature also has a direct effect on the amount of DO available to aquatic organisms. Measure temperature by submerging a thermometer for at least 2 min in a typical stream run. Repeat once and average the results.
   D. The width of the stream channel can be determined by estimating the width of the streambed that is covered by water from bank to bank. If it varies widely along the stream, estimate an average width.
   E. Local land use refers to the part of the watershed within 1/4 mi upstream of and adjacent to the site. Note which land uses are present, as well as which ones seem to be having a negative impact on the stream. Base observations on what can be seen, what was passed on the way to the stream, and, if possible, what is noticed when leaving the stream.

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Step 3 — Conduct the habitat assessment.

1. The following information describes the parameters that will be evaluated for rocky-bottom habitats. Use these definitions when completing the habitat assessment field data sheet. The first two parameters should be assessed directly at the riffles or runs that were used for the macroinvertebrate sampling. The last 8 parameters should be assessed in the entire 100-yd section of the stream.

   A. Attachment sites for macroinvertebrates are essentially the amount of living space or hard substrates (rocks, snags) available for adequate insects and snails. Many insects begin their life underwater in streams and need to attach themselves to rocks, logs, branches, or other submerged substrates. The greater the variety and number of available living spaces or attachment sites, the greater the variety of insects in the stream. Optimally, cobble should predominate, and boulders and gravel should be common. The availability of suitable living spaces for macroinvertebrates decreases as cobble becomes less abundant and boulders, gravel, or bedrock become more prevalent.

   B. Embeddedness refers to the extent to which rocks (gravel, cobble, and boulders) are surrounded by, covered with, or sunken into the silt, sand, or mud of the stream bottom. Generally, as rocks become embedded, fewer living spaces are available to macroinvertebrates and fish for shelter, spawning, and egg incubation.

Note: To estimate the percent of embeddedness, observe the amount of silt or finer sediments overlaying and surrounding the rocks. If kicking does not dislodge the rocks or cobbles, they might be greatly embedded.

   C. Shelter for fish includes the relative quantity and variety of natural structures in stream, such as fallen trees, logs, and branches; cobble and large rock; and undercut banks that are available to fish for hiding, sleeping, or feeding. A wide variety of submerged structures in the stream provide fish with many living spaces; the more living spaces in a stream, the more types of fish the stream can support.

   D. Channel alteration is a measure of large-scale changes in the shape of the stream channel. Many streams in urban and agricultural areas have been straightened, deepened (e.g., dredged), or diverted into concrete channels, often for flood control purposes. Such streams have far fewer natural habitats for fish, macroinvertebrates, and plants than do naturally meandering streams. Channel alteration is present when the stream runs through a concrete channel, when artificial embankments, riprap, and other forms of artificial bank stabilization or structures are present; when the stream is very straight for significant distances; when dams, bridges, and flow-altering structures, such as combined sewer overflow, are present; when the stream is of uniform depth due to dredging; and when other such changes have occurred. Signs that indicate the occurrence of dredging include straightened, deepened, and otherwise uniform stream channels, as well as the removal of streamside vegetation to provide dredging equipment access to the stream.

   E. Sediment deposition is a measure of the amount of sediment that has been deposited in the stream channel and the changes to the stream bottom that have occurred as a result of the deposition. High levels of sediment deposition create an unstable and continually changing environment that is unsuitable for many aquatic organisms.

      Sediments are naturally deposited in areas where the stream flow is reduced, such as in pools and bends, or where flow is obstructed. These deposits can lead to the formation of islands, shoals, or point bars (sediments that build up in the stream, usually at the beginning of a meander) or can result in the complete filling of pools. To determine whether these sediment deposits are new, look for vegetation growing on them. New sediments will not yet have been colonized by vegetation.

   F. Stream velocity and depth combinations are important to the maintenance of healthy aquatic communities. Fast water increases the amount of DO in the water, keeps pools from being filled with sediment; and helps food items like leaves, twigs, and algae move more quickly through the aquatic system. Slow water

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provides spawning areas for fish and shelters macroinvertebrates that might be washed downstream in higher stream velocities. Similarly, shallow water tends to be more easily aerated (i.e., it holds more oxygen), but deeper water stays cooler longer. The best stream habitat includes all of the following velocity or depth combinations and can maintain a wide variety of organisms.

slow (<1 ft/sec), shallow (<1.5 ft)
slow, deep
fast, deep
fast, shallow

Measure stream velocity by marking off a 10-ft section of stream run and measuring the time it takes an orange, stick, or other floating biodegradable object to float the 10 ft. Repeat 5 times, in the same 10-ft section, and determine the average time. Divide the distance (10 ft) by the average time (seconds) to determine the velocity in feet per second.

Measure the stream depth by using a stick of known length and taking readings at various points within your stream site, including riffles, runs, and pools. Compare velocity and depth at various points within the 100-yd site to see how many of the combinations are present.

G. Channel flow status is the percent of the existing channel that is filled with water. The flow status changes as the channel enlarges or as flow decreases because of dams and other obstructions, diversions for irrigation, or drought. When water does not cover much of the streambed, the living area for aquatic organisms is limited.

Note: For the following parameters, evaluate the conditions of the left and right stream banks separately. Define the left and right banks by standing at the downstream end of the study stretch and look upstream. Each bank is evaluated on a scale of 0 to 10.

H. Bank vegetation protection measures the amount of the stream bank that is covered by natural (i.e., growing wild and not obviously planted) vegetation. The root system of plants growing on stream banks helps hold soil in place, reducing erosion. Vegetation on banks provides shade for fish and macroinvertebrates and serves as a food source by dropping leaves and other organic matter into the stream. Ideally, a variety of vegetation should be present, including trees, shrubs, and grasses. Vegetation disruption can occur when the grasses and plants on the stream banks are mowed or grazed, or when the trees and shrubs are cut back or cleared.

I. Condition of banks measures erosion potential and whether the stream banks are eroded. Steep banks are more likely to collapse and suffer from erosion than are gently sloping banks and are considered to have erosion potential. Signs of erosion include crumbling, unvegetated banks, exposed tree roots, and exposed soil.

J. The riparian vegetative zone is defined as the width of natural vegetation from the edge of the stream bank. The riparian vegetative zone is a buffer zone to pollutants entering a stream from runoff. It also controls erosion and provides stream habitat and nutrient input into the stream.

Note: A wide, relatively undisturbed riparian vegetative zone reflects a healthy stream system; narrow, far less useful riparian zones occur when roads, parking lots, fields, lawns, and other artificially cultivated areas (e.g., bare soil, rock, or buildings) are near the stream bank. The presence of old fields (i.e., previously developed agricultural fields allowed to revert to natural conditions) should rate higher than fields in continuous or periodic use. In arid areas, the riparian vegetative zone can be measured by observing the width of the area dominated by riparian or water-loving plants, such as willows, marsh grasses, and cottonwood trees.

14.2.3.3 Macroinvertebrate Sampling: Muddy-Bottom Streams

In muddy-bottom streams, as in rocky-bottom streams, the goal is to sample the most productive habitat available and look for the widest variety of organisms. The most productive habitat is the one that harbors a diverse population of pollution-sensitive macroinvertebrates. Samplers should sample by using a D-frame net (see Figure 14.5) to jab at the habitat and scoop up the organisms that are dislodged. The idea is to collect a total sample that consists of 20 jabs taken from a variety of habitats.

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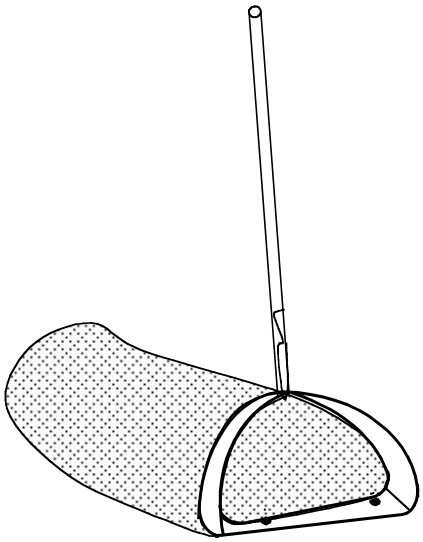

FIGURE 14.5 D-frame aquatic net. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.2.3.3.1 Muddy-Bottom Sampling Method

Use the following method of macroinvertebrate sampling in streams that have muddy-bottom substrates.

Step 1 — Determine which habitats are present.

1. Muddy-bottom streams usually have four habitats: vegetated banks margins; snags and logs; aquatic vegetation beds and decaying organic matter; and silt, sand, or gravel substrate. It is generally best to concentrate sampling efforts on the most productive habitat available, but sample other principal habitats if they are present. This ensures that as wide a variety of organisms as possible are secured. Not all habitats are present in all streams or present in significant amounts. If the sampling areas have not been preselected, determine which of the following habitats are present.

Note: Avoid standing in the stream while making habitat determinations.

A. Vegetated bank margins consist of overhanging bank vegetation and submerged root mats attached to banks. The bank margins may also contain submerged, decomposing leaf packs trapped in root wads or lining the streambanks. This is generally a highly productive habitat in a muddy stream, and it is often the most abundant type of habitat.

B. Snags and logs consist of submerged wood, primarily dead trees, logs, branches, roots, cypress knees, and leaf packs lodged between rocks or logs. This is also a very productive muddy-bottom stream habitat.

C. Aquatic vegetation beds and decaying organic matter consist of beds of submerged, green or leafy plants that are attached to the stream bottom. This habitat can be as productive as vegetated bank margins and snags and logs.

D. Silt, sand, or gravel substrate includes sandy, silty, or muddy stream bottoms; rocks along the stream bottom; and wetted gravel bars. This habitat may also contain algae-covered rocks (*Aufwuchs*). This is the least productive of the four muddy-bottom stream habitats, and it is always present in one form or another (e.g., silt, sand, mud, or gravel might predominate).

Step 2 — Determine how many times to jab in each habitat type.

1. The sampler's goal is to jab 20 times. The D-frame net (see Figure 14.5) is 1 ft wide, and a jab should be approximately 1 ft in length. Thus, 20 jabs equal 20 ft^2 of combined habitat.

A. If all 4 habitats are present in plentiful amounts, jab the vegetated banks 10 times. Divide the remaining 10 jabs amount the remaining 3 habitats.

B. If three habitats are present in plentiful amounts, and one is absent, jab the silt, or sand, or gravel substrate, the least productive habitat, five times. Divide the remaining 15 jabs between the other 2 more productive habitats.

C. If only two habitats are preset in plentiful amounts, the silt, sand, or gravel substrate will most likely be one of those habitats. Jab the silt, sand, or gravel substrate 5 times and the more productive habitat 15 times.

D. If some habitats are plentiful and others are sparse, sample the sparse habitats to the extent possible, even if you can take only one or two jabs. Take the remaining jabs from the plentiful habitats. This rule also applies if you cannot reach a habitat because of unsafe stream conditions. Jab 20 times.

Note: Because the sampler might need to make an educated guess to decide how many jabs to take in each habitat type, it is critical that each sampler note, on the field data sheet, how many jabs were taken in each habitat. This information can be used to help characterize the findings.

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Step 3 — Get into place.

1. Outside and downstream of the first sampling location (first habitat), rinse the dip net and check to make sure it does not contain any macroinvertebrates or debris from the last time it was used. Fill a bucket approximately one-third with clean stream water. Also, fill the spray bottle with clean stream water. This bottle will be used to wash the net between jabs and after sampling is completed.

Note: This method of sampling requires only one person to disturb the stream habitats. While one person is sampling, a second person should stand outside the sampling area, holding the bucket and spray bottle. After every few jabs, the sampler should hand the net to the second person, who then can rinse the net's contents into the bucket.

Step 4 — Dislodge the macroinvertebrates.

1. Approach the first sample site from downstream, and sample while walking upstream. Sample in the four habitat types as follows:
   A. Sample vegetated bank margins by jabbing vigorously with an upward motion, brushing the net against vegetation and roots along the bank. The entire jab motion should occur underwater.
   B. To sample snags and logs, hold the net with one hand under the section of submerged wood being sampled. With the other hand (which should be gloved), rub about 1 ft^2 of area on the snag or log. Scoop organisms, bark, twigs, or other organic matter dislodged into the net. Each combination of log rubbing and net scooping is one jab.
   C. To sample aquatic vegetation beds, jab vigorously with an upward motion against or through the plant bed. The entire jab motion should occur underwater.
   D. To sample a silt, sand, or gravel substrate, place the net with one edge against the stream bottom and push it forward about a foot (in an upstream direction) to dislodge the first few inches of silt, sand, gravel, or rocks. To avoid gathering a net full of mud, periodically sweep the mesh bottom of the net back and forth in the water, making sure that waters do not run over the top of the net. This will allow fine silt to rinse out of the net. When 20 jabs have been completed, rinse the net thoroughly in the bucket. If necessary, pick any clinging organisms from the net by hand and put them in the bucket.

Step 5 — Preserve the sample.

1. Look through the material in the bucket, and immediately return any fish, amphibians, or reptiles to the stream. Carefully remove large pieces of debris (leaves, twigs, and rocks) from the sample. While holding the material over the bucket, use the forceps, spray bottle, and your hands to pick, rub, and rinse the leaves, twigs, and rocks to remove any attached organisms. Use the magnifying lens and forceps to find and remove small organisms clinging to the debris. When satisfied that the material is clean, discard it back into the stream.
2. Drain the water before transferring material to the jar. This process will require two people. One person should place the net into the second bucket, like a sieve (this bucket, which has not yet been used, should be completely empty), and hold it securely. The second person can now carefully pour the remaining contents of bucket #1 onto the center of the net to drain the water and concentrate the organisms.

   Use care when pouring so that organisms are not lost over the side of the net. Use the spray bottle, forceps, sugar scoop, and gloved hands to remove all the material from bucket #1 onto the net. When satisfied that bucket #1 is empty, use your hands and the sugar scoop to transfer all the material from the net into the empty jar. The contents of the net can also be emptied directly into the jar by turning the net inside out into the jar.

   Bucket #2 captures the water and any organisms that might have fallen through the netting. As a final check, repeat the process above, but this time, pour bucket #2 over the net, into bucket #1. Transfer any organisms on the net into the jar.
3. Fill the jar (so that all material is submerged) with alcohol. Put the lid tightly back onto the jar, and gently turn the jar upside down two or three times to distribute the alcohol and remove air bubbles.
4. Complete the sampling station ID tag (see Figure 14.6). Be sure to use a pencil, since a pen's ink will run in the alcohol. The tag includes your station number, the stream, and location (e.g., upstream from a road crossing), date, time, and the names of the members of the collecting crew. Place the ID tag into the sample container, written side

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Station ID Tag

Station # _____

Stream _____

Location _____

Date/Time _____

Team Members: _____

_____

_____

FIGURE 14.6 Station ID tag. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

facing out, so that identification can be seen clearly.

Note: To prevent samples from being mixed up, samplers should place the ID tag inside the sample jar.

14.2.3.3.2 Muddy-Bottom Stream Habitat Assessment

The muddy-bottom stream habitat assessment (which includes measuring general characteristics and local land use) is conducted in a 100-yard section of the stream that includes the habitat areas from which organisms were collected.

Note: As previously mentioned, when using a field data sheet (habitat assessment field data sheet), assume that the sampling team is using either the standard forms provided by the EPA, USGS, state water control authorities, or generic forms put together by the sampling team. The source of the form and exact type of form are not important. Some type of data recording field sheet should be employed to record pertinent data.

Step 1 — Delineate the habitat assessment boundaries.

1. Begin by identifying the most downstream point that was sampled for macroinvertebrates. Using your tape measure or twine, mark off a 100-yd section extending 25 yd below the downstream sampling point and about 75 yd upstream.
2. Complete the identifying information on the field data sheet for the habitat assessment site. On the stream sketch, be as detailed as possible, and be sure to note which habitats were sampled.

Step 2 — Record general characteristics and local land use on the data field sheet.

1. For safety reasons, as well as to protect the stream habitat, it is best to estimate these characteristics rather than actually wade into the stream to measure them. For instructions on completing these sections of the field data sheet, see the rocky-bottom habitat assessment instructions.

Step 3 — Conduct the habitat assessment.

1. The following information describes the parameters to be evaluated for muddy-bottom habitats. Use these definitions when completing the habitat assessment field data sheet.
   A. Shelter for fish and attachment sites for macroinvertebrates are essentially the amount of living space and shelter (rocks, snags, and undercut banks) available for fish, insects, and snails. Many insects attach themselves to rocks, logs, branches, or other submerged substrates. Fish can hide or feed in these areas. The greater the variety and number of available shelter sites or attachment sites, the greater the variety of fish and insects in the stream.

Note: Many of the attachment sites result from debris falling into the stream from the surrounding vegetation. When debris first falls into the water, it is termed new fall, and it has not yet been broken down by microbes (conditioned) for macroinvertebrate colonization. Leaf material or debris that is conditioned is called old

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fall. Leaves that have been in the stream for some time lose their color, turn brown or dull yellow, become soft and supple with age, and might be slimy to the touch. Woody debris becomes blackened or dark in color; smooth bark becomes coarse and partially disintegrated, creating holes and crevices. It might also be slimy to the touch.

B. Poor substrate characterization evaluates the type and condition of bottom substrates found in pools. Pools with firmer sediment types (e.g., gravel, sand) and rooted aquatic plants support a wider variety of organisms than do pools with substrates dominated by mud or bedrock and no plants. In addition, a pool with one uniform substrate type will support far fewer types of organisms than will a pool with a wide variety of substrate types.
C. Pool variability rates the overall mixture of pool types found in the stream according to size and depth. The four basic types of pools are large-shallow, large-deep, small-shallow, and small-deep. A stream with many pool types will support a wide variety of aquatic species. Rivers with low sinuosity (few bends) and monotonous pool characteristics do not have sufficient quantities and types of habitats to support a diver's aquatic community.
D. Channel alteration (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-D).
E. Sediment deposition (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-E).
F. Channel sinuosity evaluates the sinuosity or meandering of the stream. Streams that meander provide a variety of habitats (such as pools and runs) and stream velocities and reduce the energy from current surges during storm events. Straight stream segments are characterized by even stream depth and unvarying velocity, and they are prone to flooding. To evaluate this parameter, imagine how much longer the stream would be if it were straightened.
G. Channel flow status (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-G).
H. Bank vegetative protection (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-H).
I. Condition of banks (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-I).
J. The riparian vegetative zone width (see Section 14.2.3.2.2, Rocky-Bottom Habitat Assessment, Step 3, 1-J).

Note: Whenever stream sampling is to be conducted, it is a good idea to have a reference collection on hand. A reference collection is a sample of locally found macroinvertebrates that have been identified, labeled, and preserved in alcohol. The program advisor, along with a professional biologist/entomologist, should assemble the reference collection, properly identify all samples, preserve them in vials, and label them. This collection may then be used as a training tool and, in the field, as an aid in macroinvertebrate identification.

14.2.4 Postsampling Routine

After completing the stream characterization and habitat assessment, make sure that all of the field data sheets have been completed properly and that the information is legible. Be sure to include the site's identifying name and the sampling date on each sheet. This information will function as a quality control element.

Before leaving the stream location, make sure that all sampling equipment or devices have been collected and rinsed properly. Double-check to see that sample jars are tightly closed and properly identified. All samples, field sheets, and equipment should be returned to the team leader at this point. Keep a copy of the field data sheets for comparison with future monitoring trips and for personal records.

The next step is to prepare for macroinvertebrate laboratory work. This step includes all the work needed to set up a laboratory for processing samples into subsamples and identifying macroinvertebrates to the family level. A professional biologist, entomologist, or freshwater ecologist or the professional advisor should supervise the identification procedure. (Note: The actual laboratory procedures after the sampling and collecting phase are beyond the scope of this text.)

14.2.4.1 Sampling Devices

In addition to the sampling equipment mentioned previously, it may be desirable to employ, depending on stream conditions, the use of other sampling devices. Additional sampling devices commonly used and discussed in the following sections include DO and temperature monitors, sampling nets (including the D-frame aquatic net), sediment samplers (dredges), plankton samplers, and Secchi disks.

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14.2.4.1.1 Dissolved Oxygen and Temperature Monitor

(Note: The methods described in this section are approved by the EPA. Coverage that is more detailed is available in *Standard Methods for the Examination of Water and Wastewater*, 20th ed., American Public Health Association, Washington, D.C., 1998, pp. 4–129.)

As mentioned, the DO content of a stream sample can provide the investigator with vital information, as DO content reflects the stream's ability to maintain aquatic life.

14.2.4.1.2 The Winkler DO with Azide Modification Method

The Winkler DO with azide modification method is commonly used to measure DO content. The Winkler Method is best suited for clean waters. It can be used in the field but is better suited for laboratory work where better accuracy may be achieved. The Winkler method adds a divalent manganese solution followed by a strong alkali to a 300 mL BOD bottle of stream water sample. Any DO rapidly oxidizes an equivalent amount of divalent manganese to basic hydroxides of higher balance states. When the solution is acidified in the presence of iodide, oxidized manganese again reverts to the divalent state; iodine, which is equivalent to the original DO content of the sample, is liberated. The amount of iodine is then determined by titration with a standard, usually thiosulfate, solution.

Fortunately for the field biologist, this is the age of miniaturized electronic circuit components and devices; it is not too difficult to obtain portable electronic measuring devices for DO and temperature that are of quality construction and have better than moderate accuracy. These modern electronic devices are usually suitable for laboratory and field use. The device may be subjected to severe abuse in the field. Therefore, the instrument must be durable, accurate, and easy to sue. Several quality DO monitors are available commercially.

When using a DO monitor, it is important to calibrate (standardize) the meter prior to use. Calibration procedures can be found in *Standard Methods* (latest edition) or in the manufacturer's instructions for the meter to be used. Determining the air temperature, the DO at saturation for that temperature, and then adjusting the meter so that it reads the saturation value usually accomplish meter calibration. After calibration, the monitor is ready for use. As mentioned, all recorded measurements, including water temperatures and DO readings, should be entered in a field notebook.

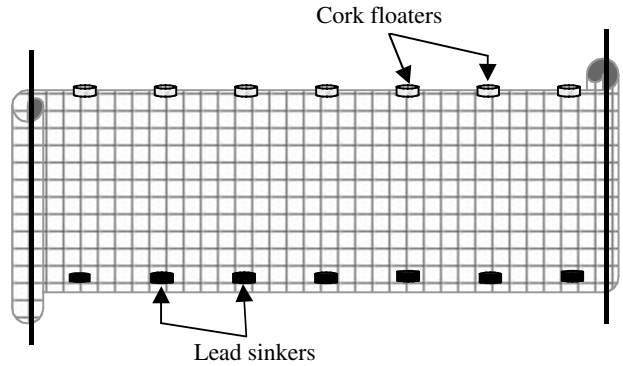

FIGURE 14.7 Two-person seine net. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.2.4.1.3 Sampling Nets

A variety of sampling nets are available for use in the field. The two-person seine net shown in Figure 14.7 is 20 × 4 ft deep with 1/8 in. mesh and is utilized to collect a variety of organisms. Two people, each holding one end and then walking upstream, use it. Small organisms are easily collected by this method.

Dip nets are used to collect organisms in shallow streams. The Surber sampler (collects macroinvertebrates stirred up from the bottom; see Figure 14.8) can be used to obtain a quantitative sample (number of organisms/square feet). It is designed for sampling riffle areas in steams and rivers up to a depth of about 450 mm (18 in.). It consists of two folding stainless steel frames set at right angles to each other. The frame is placed on the bottom, with the net extending downstream. Using a hand or a rake, all sediment enclosed by the frame is dislodged. All organisms are caught in the net and transferred to another vessel for counting.

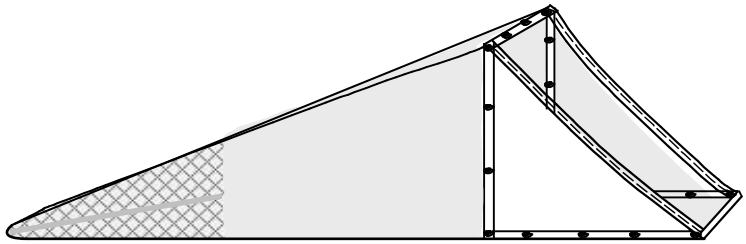

FIGURE 14.8 Surber sampler. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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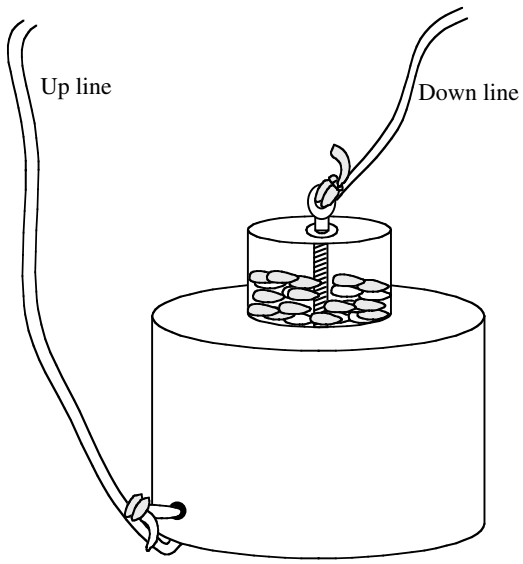

FIGURE 14.9 Homemade dredge. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

The D-frame aquatic dip net (see Figure 14.5) is ideal for sweeping over vegetation or for use in shallow streams.

14.2.4.1.4 Sediment Samplers (Dredges)

A sediment sampler or dredge is designed to obtain a sample of the bottom material in a slow-moving stream and the organisms in it. The simple homemade dredge shown in Figure 14.9 works well in water too deep to sample effectively with handheld tools. The homemade dredge is fashioned from a #3 coffee can and a smaller can (see Figure 14.9) with a tight fitting plastic lid (peanut cans work well).

In using the homemade dredge, first invert it under water so the can fills with water and no air is trapped. Then lower the dredge as quickly as possible with the down line. The idea is to bury the open end of the coffee can in the bottom. Quickly pull the up line to bring the can to the surface with a minimum loss of material. Dump the contents into a sieve or observation pan to sort. It works best in bottoms composed of sediment, mud, sand, and small gravel.

By using the bottom sampling dredge, a number of different analyses can be made. Because the bottom sediments represent a good area in which to find macroinvertebrates and benthic algae, the communities of organisms living on or in the bottom can be easily studied quantitatively and qualitatively. A chemical analysis of the bottom sediment can be conducted to determine what chemicals are available to organisms living in the bottom habitat.

14.2.4.1.5 Plankton Sampler

(Note: More detailed information on plankton sampling can be found in *Plankton Sampling*, Robert V. Annis Water Resource Institute, Grand Valley state University, 2000, pp. 1–3.)

Plankton (meaning to drift) are distributed through the stream and, in particular, in pool areas. They are found at all depths and are comprised of plant (phytoplankton) and animal (zooplankton) forms. Plankton show a distribution pattern that can be associated with the time of day and seasons.

There are three fundamental sizes of plankton: nannoplankton, microplankton, and macroplankton. The smallest are nannoplankton and range in size from 5 to 60 μm (one-millionth of a meter). Because of their small size, most nannoplankton will pass through the pores of a standard sampling net. Special fine mesh nets can be used to capture the larger nannoplankton.

Most planktonic organisms fall into the microplankton or net plankton category. The sizes range from the largest nannoplankton to about 2 mm (thousandths of a meter). Nets of various sizes and shapes are used to collect microplankton. The nets collect the organism by filtering water through fine meshed cloth. The plankton nets on the vessels are used to collect microplankton.

The third group of plankton, as associated with size, is called macroplankton. They are visible to the naked eye. The largest can be several meters long.

The plankton net or sampler (see Figure 14.10) is a device that makes it possible to collect phytoplankton and

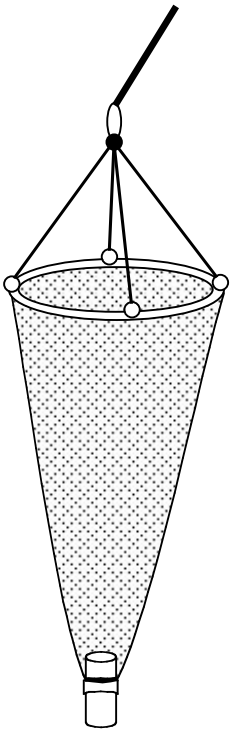

FIGURE 14.10 Plankton net. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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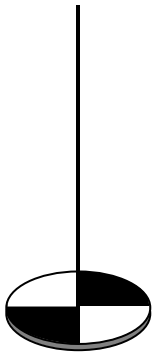

FIGURE 14.11 Secchi disk. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

zooplankton samples. For quantitative comparisons of different samples, some nets have a flowmeter used to determine the amount of water passing through the collecting net.

The plankton net or sampler provides a means of obtaining samples of plankton from various depths so that distribution patterns can be studied. Considering the depth of the water column that is sampled can make quantitative determinations. The net can be towed to sample plankton at a single depth (horizontal tow) or lowered into the water to sample the water column (vertical tow). Another possibility is oblique tows where the net is lowered to a predetermined depth and raised at a constant rate as the vessel moves forward.

After towing and removal from the stream, the sides of the net are rinsed to dislodge the collected plankton. If a quantitative sample is desired, a certain quantity of water is collected. If the plankton density is low, then the sample may be concentrated using a low-speed centrifuge or some other filtering device. A definite volume of the sample is studied under the compound microscope for counting and identifying plankton.

14.2.4.1.6 Secchi Disk

For determining water turbidity or degree of visibility in a stream, a Secchi disk is often used (Figure 14.11). The Secchi disk originated with Father Pietro Secchi, an astrophysicist and scientific advisor to the Pope, who was requested to measure transparency in the Mediterranean Sea by the head of the Papal Navy. Secchi used some white disks to measure the clarity of water in the Mediterranean in April 1865. Various sizes of disks have been used since that time, but the most frequently used disk is an 8-in. diameter metal disk painted in alternate black and white quadrants.

The disk shown in Figure 14.11 is 20 cm in diameter; it is lowered into the stream using the calibrated line. To use the Secchi disk properly, it should be lowered into the stream water until it is no longer visible. At the point where it is no longer visible, a measurement of the depth is taken. This depth is called the Secchi disk transparency light extinction coefficient. The best results are usually obtained after early morning and before late afternoon.

14.2.4.1.7 Miscellaneous Sampling Equipment

Several other sampling tools or devices are available for use in sampling a stream. For example, consider the standard sand-mud sieve. Generally made of heavy-duty galvanized 1/8″ mesh screen supported by a water-sealed 24 × 15 × 3 in. wood frame, this device is useful for collecting burrowing organisms found in soft bottom sediments. Moreover, no stream sampling kit would be complete without a collecting tray, collecting jars of assorted sizes, heavy-duty plastic bags, small pipets, large two-ounce pipets, fine mesh straining net, and black china marking pencil. In addition, depending upon the quantity of material to be sampled, it is prudent to include several 3- and 5-gal collection buckets in the stream sampling field kit.

14.2.5 The Bottom Line on Biological Sampling

This discussion has stressed the practice of biological monitoring, employing the use of biotic indices as key measuring tools. We emphasized biotic indices not only for their simplicity of use, but also for the relative accuracy they provide, although their development and use can sometimes be derailed. The failure of a monitoring protocol to assess environmental condition accurately or to protect running waters usually stems from conceptual, sampling, or analytical pitfalls. Biotic indices can be combined with other tools for measuring the condition of ecological systems in ways that enhance or hinder their effectiveness. The point is, like any other tool, they can be misused. However, the fact that biotic indices can be, and are, misused does not mean that the indices' approach itself is useless.

To ensure that the biotic indices approach is not useless, it is important for the practicing freshwater ecologist and water sampler to remember a few key guidelines:

1. Sampling everything is not the goal. As Botkin et al. note, biological systems are complex and unstable in space and time, and samplers often feel compelled to study all components of this variation. Complex sampling programs proliferate. However, every study need not explore everything. Freshwater samplers and monitors should avoid the temptation to sample all the unique habitats and phenomena that make freshwater monitoring so interesting. Concentration should be placed on the central components of a clearly defined research agenda (a sampling or monitoring protocol) — detecting

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and measuring the influences of human activities on the water body's ecological system.[12]

2. In regard to the influence of human activities on the water body's ecological system, we must see protecting biological conditions as a central responsibility of water resource management. One thing is certain. Until biological monitoring is seen as essential to track attainment of that goal and biological criteria as enforceable standards mandated by the CWA, life in the nation's freshwater systems will continue to decline.

Biomonitoring is only one of several tools available to the water practitioner. No matter the tool employed, all results depend upon proper biomonitoring techniques. Biological monitoring must be designed to obtain accurate results – present approaches need to be strengthened. In addition, "the way it has always been done" must be reexamined, and efforts must be undertaken to do what works to keep freshwater systems alive. We can afford nothing less.

14.3 WATER QUALITY MONITORING (DRINKING WATER)

When we speak of water quality monitoring, we refer to monitoring practice based on three criteria:

1. To ensure to the extent possible that the water is not a danger to public health
2. To ensure that the water provided at the tap is as aesthetically pleasing as possible
3. To ensure compliance with applicable regulations

To meet these goals, all public systems must monitor water quality to some extent. The degree of monitoring employed is dependent on local needs and requirements and the type of water system; small water systems using good-quality water from deep wells may only need to provide occasional monitoring, but systems using surface water sources must test water quality frequently.[13]

Drinking water must be monitored to provide adequate control of the entire water drawing, treatment, or conveyance system. Adequate control is defined as monitoring employed to assess the present level of water quality, so action can be taken to maintain the required level (whatever that might be).

We define water quality monitoring as the sampling and analysis of water constituents and conditions. When we monitor, we collect data. As a monitoring program is developed, deciding the reasons for collecting the information is important. The reasons are defined by establishing a set of objectives that includes a description of who will collect the information.

It may come as a surprise to know that today the majority of people collecting data are not water and wastewater operators; many are volunteers. These volunteers have a stake in their local stream, lake, or other water body, and in many cases they are proving they can successfully carry out a water quality-monitoring program.

14.3.1 Is the Water Good or Bad?

(Note: Much of the information presented in the following sections is based on EPA's 2.841B97003 *Volunteer Stream Monitoring: A Methods Manual*, 1997, and on personal experience.)

To answer the question, "Is the water good or bad?," we must consider two factors. First, we return to the basic principles of water quality monitoring — sampling and analyzing water constituents and conditions. These constituents include:

1. Introduced pollutants, such as pesticides, metals, and oil
2. Constituents found naturally in water that can nevertheless be affected by human sources, such as DO, bacteria, and nutrients

The magnitude of their effects is influenced by properties such as pH and temperature. For example, temperature influences the quantity of dissolved oxygen that water is able to contain, and pH affects the toxicity of ammonia.

The second factor to be considered is that the only valid way to answer this question is to conduct a test that must be compared to some form of water quality standards. If simply assigning a good and bad value to each test factor were possible, the meters and measuring devices in water quality test kits would be much easier to make. Instead of fine graduations, they could simply have a good and a bad zone.

Water quality — the difference between good and bad water — must be interpreted according to the intended use of the water. For example, the perfect balance of water chemistry that assures a sparkling clear, sanitary swimming pool would not be acceptable as drinking water and would be a deadly environment for many biota. Consider Table 14.3.

In another example, widely different levels of fecal coliform bacteria are considered acceptable, depending on the intended use of the water.

TABLE 14.3
Total Residual Chlorine (mg/L)

0.06.	Toxic to striped bass larvae
0.31	Toxic to white perch larvae
0.5–1.0	Typical drinking water residual
1.0–3.0	Recommended for swimming pools

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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State and local water quality practitioners as well as volunteers have been monitoring water quality conditions for many years. In fact, until the past decade or so (until biological monitoring protocols were developed and began to take hold), water quality monitoring was generally considered the primary way of identifying water pollution problems. Today, professional water quality practitioners and volunteer program coordinators alike are moving toward approaches that combine chemical, physical, and biological monitoring methods to achieve the best picture of water quality conditions.

Water quality monitoring can be used for many purposes:

1. To identify whether waters are meeting designated uses — All states have established specific criteria (limits on pollutants) identifying what concentrations of chemical pollutants are allowable in their waters. When chemical pollutants exceed maximum or minimum allowable concentrations, waters may no longer be able to support the beneficial uses, such as fishing, swimming, and drinking, for which they have been designated (see Table 14.4). Designated or intended uses and the specific criteria that protect them (along with antidegredation statements that say waters should not be allowed to deteriorate below existing or anticipated uses) together form water quality standards. State water quality professionals assess water quality by comparing the concentrations of chemical pollutants found in streams to the criteria in the state's standards, and judge whether streams are meeting their designated uses

   Water quality monitoring, however, might be inadequate for determining whether aquatic life needs are being met in a stream. While some constituents (such as dissolved oxygen and temperature) are important to maintaining healthy fish and aquatic insect populations, other factors (such as the physical structure of the stream and the condition of the habitat) play an equal or greater role. Biological monitoring methods are generally better suited to determine whether aquatic life is supported.
2. To identify specific pollutants and sources of pollution — Water quality monitoring helps link sources of pollution to water body quality problems because it identifies specific problem pollutants. Since certain activities tend to generate certain pollutants (bacteria and nutrients are more likely to come from an animal feedlot than an automotive repair shop), a tentative link to what would warrant further investigation or monitoring can be formed.
3. To determine trends — Chemical constituents that are properly monitored (i.e., using consistent time of day and on a regular basis using consistent methods) can be analyzed for trends over time.
4. To screen for impairment — Finding excessive levels of one or more chemical constituents can serve as an early warning screen for potential pollution problems.

TABLE 14.4
Fecal Coliform Bacteria per 100 mL of Water

Desirable	Permissible	Type of Water Use
0	0	Potable and well water (for drinking)
<200	<1000	Primary contact water (for swimming)
<1000	<5000	Secondary contact water (boating and fishing)

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.3.2 State Water Quality Standards Programs

Each state has a program to set standards for the protection of each body of water within its boundaries. Standards for each body of water are developed that:

1. Depend on the water's designated use
2. Are based on EPA national water quality criteria and other scientific research into the effects of specific pollutants on different types of aquatic life and on human health
3. May include limits based on the biological diversity of the body of water (the presence of food and prey species)

State water quality standards set limits on pollutants and establish water quality levels that must be maintained for each type of water body based on its designated use.

Resources for this type of information include:

1. EPA Water Quality Criteria Program
2. U.S. Fish and Wildlife Service Habitat Suitability Index Models (for specific species of local interest)

Monitoring test results can be plotted against these standards to provide a focused, relevant, required assessment of water quality.

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TABLE 14.5
Water Quality Problems and Pollution Sources

Source	Common Associated Chemical Pollutants
Cropland	Turbidity, phosphorus, nitrates, temperature, total solids
Forestry harvest	Turbidity, temperature, total solids
Grazing land	Fecal bacteria, turbidity, phosphorus
Industrial discharge	Temperature, conductivity, total solids, toxics, pH
Mining	pH, alkalinity, total dissolved solids
Septic systems	Fecal bacteria, (i.e., *Escherichia coli, enterococcus*), nitrates, DO and BOD, conductivity, temperature.
Sewage treatment	DO and BOD, turbidity, conductivity, phosphorus, nitrates, fecal bacteria, temperature, total solids, pH
Construction	Turbidity, temperature, DO and BOD, total solids, toxics
Urban runoff	Turbidity, phosphorus, nitrates, temperature, conductivity, DO and BOD

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.3.3 Designing a Water Quality Monitoring Program

The first step in designing a water quality-monitoring program is to determine the purpose for the monitoring. This aids in selection of the parameters to monitor. This decision should be based on factors that include:

1. Types of water quality problems and pollution sources that will likely be encountered (see Table 14.5)
2. Cost of available monitoring equipment
3. Precision and accuracy of available monitoring equipment
4. Capabilities of monitors

(Note: We discuss the parameters most commonly monitored by drinking water practitioners in streams (i.e., we assume, for illustration and discussion purposes, that our water source is a surface water stream) in detail in this section. They include DO, BOD, temperature, pH, turbidity, total orthophosphate, nitrates, total solids, conductivity, total alkalinity, fecal bacteria, apparent color, odor, and hardness. When monitoring water supplies under the Safe Drinking Water Act or the National Pollutant Discharge Elimination System [NPDES], utilities must follow test procedures approved by the USEPA for these purposes. Additional testing requirements under these and other federal programs are published as amendments in the Federal Register.)

Except when monitoring discharges for specific compliance purposes, a large number of approximate measurements can provide more useful information than one or two accurate analyses. Because water quality and chemistry continually change, making periodic, representative measurements and observations that indicate the range of water quality is necessary, rather than testing the quality at any single moment. The more complex a water system, the more time required to observe, understand, and draw conclusions regarding the cause and effect of changes in the particular system.

14.3.4 General Preparation and Sampling Considerations

(Note: The sections that follow detail specific equipment considerations and analytical procedures for each of the most common water quality parameters.)

Sampling devices should be corrosion resistant, easily cleaned, and capable of collecting desired samples safely and in accordance with test requirements. Whenever possible, assign a sampling device to each sampling point. Sampling equipment must be cleaned on a regular schedule to avoid contamination.

Note: Some tests require special equipment to ensure the sample is representative. DO and fecal bacteria sampling require special equipment and/or procedures to prevent collection of nonrepresentative samples.

Reused sample containers and glassware must be cleaned and rinsed before the first sampling run and after each run by following Method A or Method B described below. The most suitable method depends on the parameter being measured.

14.3.4.1 Method A: General Preparation of Sampling Containers

Use the following method when preparing all sample containers and glassware for monitoring conductivity, total solids, turbidity, pH, and total alkalinity. Wearing latex gloves:

1. Wash each sample bottle or piece of glassware with a brush and phosphate-free detergent.
2. Rinse three times with cold tap water.
3. Rinse three times with distilled or deionized water.

14.3.4.2 Method B: Acid Wash Procedures

Use this method when preparing all sample containers and glassware for monitoring nitrates and phosphorus. Wearing latex gloves:

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1. Wash each sample bottle or piece of glassware with a brush and phosphate-free detergent.
2. Rinse three times with cold tap water.
3. Rinse with 10% hydrochloric acid.
4. Rinse three times with deionized water.

14.3.5 Sample Types

Two types of samples are commonly used for water quality monitoring: grab samples and composite samples. The type of sample used depends on the specific test, the reason the sample is being collected, and the applicable regulatory requirements.

Grab samples are taken all at once, at a specific time and place. They are representative only of the conditions at the time of collection.

Grab samples must be used to determine pH, total residual chlorine (TRC), DO, and fecal coliform concentrations. Grab samples may also be used for any test, which does not specifically prohibit their use.

Note: Before collecting samples for any test procedure, it is best to review the sampling requirements of the test.

Composite samples consist of a series of individual grab samples collected over a specified period in proportion to flow. The individual grab samples are mixed together in proportion to the flow rate at the time the sample was collected to form the composite sample. This type of sample is taken to determine average conditions in a large volume of water whose properties vary significantly over the course of a day.

14.3.6 Collecting Samples from a Stream

In general, sample away from the streambank in the main current. Never sample stagnant water. The outside curve of the stream is often a good place to sample because the main current tends to hug this bank. In shallow stretches, carefully wade into the center current to collect the sample.

A boat is required for deep sites. Try to maneuver the boat into the center of the main current to collect the water sample.

When collecting a water sample for analysis in the field or at the lab, follow the steps below.

14.3.6.1 Whirl-pak® Bags

To collect water samples using Whirl-pak bags, use the following procedures:

1. Label the bag with the site number, date, and time.
2. Tear off the top of the bag along the perforation above the wire tab just before sampling. Avoid touching the inside of the bag. If you accidentally touch the inside of the bag, use another one.
3. Wading — Try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that contains bottom sediment. Stand facing upstream. Collect the water samples in front of you.

   Boat — Carefully reach over the side and collect the water sample on the upstream side of the boat.
4. Hold the two white pull-tabs in each hand and lower the bag into the water on your upstream side with the opening facing upstream. Open the bag midway between the surface and the bottom by pulling the white pull-tabs. The bag should begin to fill with water. You may need to "scoop" water into the bag by drawing it through the water upstream and away from you. Fill the bag no more than 3/4 full!
5. Lift the bag out of the water. Pour out excess water. Pull on the wire tabs to close the bag. Continue holding the wire tabs and flip the bag over at least four to five times quickly to seal the bag. Do not try to squeeze the air out of the top of the bag. Fold the ends of the bag, being careful not to puncture the bag. Twist them together, forming a loop.
6. Fill in the bag number or site number on the appropriate field data sheet. This is important. It is the only way the lab specialist will know which bag goes with which site.
7. If samples are to be analyzed in a lab, place the sample in the cooler with ice or cold packs. Take all samples to the lab.

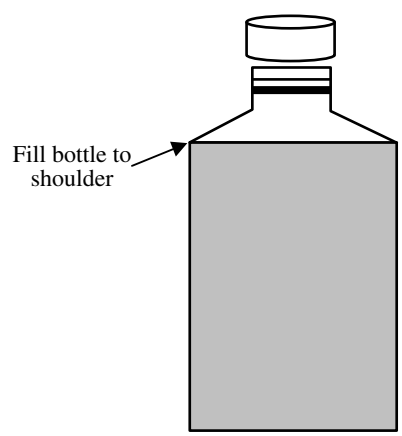

FIGURE 14.12 Sampling bottle. Filling to shoulder assures collecting enough sample. Do not overfill. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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14.3.6.2 Screw-Cap Bottles

To collect water samples using screw-cap bottles, use the following procedures (see Figure 14.12):

1. Label the bottle with the site number, date, and time.
2. Remove the cap from the bottle just before sampling. Avoid touching the inside of the bottle or the cap. If you accidentally touch the inside of the bottle, use another one.
3. Wading — Try to disturb as little bottom sediment as possible. In any case, be careful not to collect water that has sediment from bottom disturbance. Stand facing upstream. Collect the water sample on your upstream side, in front of you. You may also tape your bottle to an extension pole to sample from deeper water.
   Boat — Carefully reach over the side and collect the water sample on the upstream side of the boat.
4. Hold the bottle near its base and plunge it (opening downward) below the water surface. If you are using an extension pole, remove the cap, turn the bottle upside down, and plunge it into the water, facing upstream. Collect a water sample 8 to 12 in. beneath the surface, or midway between the surface and the bottom if the stream reach is shallow.
5. Turn your bottle underwater into the current and away from you. In slow moving stream reaches, push the bottle underneath the surface and away from you in the upstream direction.
6. Leave a 1-in. air space (except for DO and BOD samples). Do not fill the bottle completely (so that the sample can be shaken just before analysis). Recap the bottle carefully, remembering not to touch the inside.
7. Fill in the bottle number or site number on the appropriate field data sheet. This is important because it tells the lab specialist which bottle goes with which site.
8. If the samples are to be analyzed in the lab, place them in the cooler for transport to the lab.

14.3.7 Sample Preservation and Storage

Samples can change very rapidly. However, no single preservation method will serve for all samples and constituents. If analysis must be delayed, follow the instructions for sample preservation and storage listed in *Standard Methods,* or those specified by the laboratory that will eventually process the samples (see Table 14.6). In general, handle the sample in a way that prevents changes from biological activity, physical alterations, or chemical reactions. Cool the sample to reduce biological and chemical reactions. Store in darkness to suspend photosynthesis. Fill the sample container completely to prevent the loss of dissolved gases. Metal cations, such as iron and lead, and suspended particles may adsorb onto container surfaces during storage.

TABLE 14.6
Recommended Sample Storage and Preservation Techniques

Test Factor	Container Type	Preservation	Max. Storage Time Recommended/Regulatory
Alkalinity	P, G	Refrigerate	24 h/14 d
BOD	P, G	Refrigerate	6 h/48 h
Conductivity	P, G	Refrigerate	28 d/28 d
Hardness	P, G	Lower pH to <2	6 mos/6 mos
Nitrate	P, G	Analyze ASAP	48 h/48 h
Nitrite	P, G	Analyze ASAP	none/48 h
Odor	G	Analyze ASAP	6 h/N/R
Oxygen, dissolved			
Electrode	G	Immediately analyze	0.5 h/stat
Winkler	G	Fix Immediately analyze	8-h/8 h
pH	P, G	Immediately analyze	2 h/stat
Phosphate	G(A)	Filter immediately	48 h/N/R; refrigerate
Salinity	G, was seal	Immediately analyze or use was seal	6 mos/N/R
Temperature	P, G	Immediately analyze	stat/stat
Turbidity	P, G	Analyze same day or store in dark up to 24 h, refrigerate	24 h/48 h

Note: P = plastic; G = glass; N/R = no result.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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14.3.8 Standardization of Methods

References used for sampling and testing must correspond to those listed in the most current federal regulation. For the majority of tests, to compare the results of either different water quality monitors or the same monitors over the course of time requires some form of standardization of the methods. The American Public Health Association (APHA) recognized this requirement in 1899 when it appointed a committee to draw up standard procedures for the analysis of water. The report (published in 1905) constituted the first edition of what is now known as *Standard Methods.* This book is now in its 20th edition and serves as the primary reference for water testing methods and the basis for most EPA-approved methods.

14.4 TEST METHODS (DRINKING WATER AND WASTEWATER)

(Note: The material presented in this section is based on personal experience and adaptations from Standard *Methods*, *Federal Register*, and *The Monitor's Handbook*, LaMotte Company, Chestertown, MD, 1992.)

Descriptions of general methods to help you understand how each works in specific test kits follow. Always use the specific instructions included with the equipment and individual test kits.

Most water analyses are conducted either by titrimetric analyses or colorimetric analyses. Both methods are easy to use and provide accurate results.

14.4.1 Titrimetric Methods

Titrimetric analyses are based on adding a solution of know strength (the titrant, which must have an exact known concentration) to a specific volume of a treated sample in the presence of an indicator. The indicator produces a color change indicating the reaction is complete. Titrants are generally added by a Titrator (microburet) or a precise glass pipette.

14.4.2 Colorimetric Methods

Colorimetric standards are prepared as a series of solutions with increasing known concentrations of the constituent to be analyzed. Two basic types of colorimetric tests are commonly used:

1. The pH is a measure of the concentration of hydrogen ions (the acidity of a solution) determined by the reaction of an indicator that varies in color, depending on the hydrogen ion levels in the water.
2. Tests that determine a concentration of an element or compound are based on Beer's law. Simply, this law states that the higher the concentration of a substance, the darker the color produced in the test reaction and the more light absorbed. Assuming a constant viewpath, the absorption increases exponentially with concentration.

14.4.3 Visual Methods

The Octet comparator uses standards that are mounted in a plastic comparator block. It employs eight permanent translucent color standards and built-in filters to eliminate optical distortion. The sample is compared using either of two viewing windows. Two devices that can be used with the comparator are the B-color reader, which neutralizes color or turbidity in water samples, and viewpath, which intensifies faint colors of low concentrations for easy distinction.

14.4.4 Electronic Methods

Although the human eye is capable of differentiating color intensity, interpretation is quite subjective. Electronic colorimeters consist of a light source that passes through a sample and is measured by a photodetector with an analog or digital readout.

Besides electronic colorimeters, specific electronic instruments are manufactured for lab and field determination of many water quality factors, including pH, total dissolved solids and conductivity, DO, temperature, and turbidity.

14.4.5 Dissolved Oxygen Testing

(Note: In this section and the sections that follow, we discuss several water quality factors that are routinely monitored in drinking water operations. We do not discuss the actual test procedures to analyze each water quality factor; refer to the latest edition of *Standard Methods* for the correct procedure to use in conducting these tests.)

A stream system used as a source of water produces and consumes oxygen. It gains oxygen from the atmosphere and from plants because of photosynthesis. Because of running water's churning, it dissolves more oxygen than does still water, such as in a reservoir behind a dam. Respiration by aquatic animals, decomposition, and various chemical reactions consume oxygen.

Oxygen is actually poorly soluble in water. Its solubility is related to pressure and temperature. In water supply systems, DO in raw water is considered the necessary element to support life of many aquatic organisms. From the drinking water practitioner's point of view, DO is an important indicator of the water treatment process, and an important factor in corrosiveness.

Wastewater effluent often contains organic materials that are decomposed by microorganisms that use oxygen in the process. (The amount of oxygen consumed by these organisms in breaking down the waste is known as the BOD. We include a discussion of BOD and how to monitor

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TABLE 14.7
Maximum DO Concentrations vs. Temperature Variations

Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)
0	14.60	23	8.56
1	14.19	24	8.40
2	13.81	25	8.24
3	13.44	26	8.09
4	13.09	27	7.95
5	12.75	28	7.81
6	12.43	29	7.67
7	12.12	30	7.54
8	11.83	31	7.41
9	11.55	32	7.28
10	11.27	33	7.16
11	11.01	34	7.05
12	10.76	35	6.93
13	10.52	36	6.82
14	10.29	37	6.71
15	10.07	38	6.61
16	9.85	39	6.51
17	9.65	40	6.41
18	9.45	41	6.31
19	9.26	42	6.22
20	9.07	43	6.13
21	8.90	44	6.04
22	8.72	45	5.95

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

it later.) Other sources of oxygen-consuming waste include stormwater runoff from farmland or urban streets, feedlots, and failing septic systems.

Oxygen is measured in its dissolved form as DO. If more oxygen is consumed than produced, DO levels decline and some sensitive animals may move away, weaken, or die.

DO levels fluctuate over a 24-h period and seasonally. They vary with water temperature and altitude. Cold water holds more oxygen than warm water (see Table 14.7), and water holds less oxygen at higher altitudes. Thermal discharges (e.g., water used to cool machinery in a manufacturing plant or a power plant) raise the temperature of water and lower its oxygen content. Aquatic animals are most vulnerable to lowered DO levels in the early morning on hot summer days when stream flows are low, water temperatures are high, and aquatic plants have not been producing oxygen since sunset.

14.4.5.1 Sampling and Equipment Considerations

In contrast to lakes, where DO levels are most likely to vary vertically in the water column, changes in DO in rivers and streams move horizontally along the course of the waterway. This is especially true in smaller, shallow streams. In larger, deeper rivers, some vertical stratification of DO might occur. The DO levels in and below riffle areas, waterfalls, or dam spillways are typically higher than those in pools and slower-moving stretches. If you wanted to measure the effect of a dam, sampling for DO behind the dam, immediately below the spillway, and upstream of the dam would be important. Because DO levels are critical to fish, a good place to sample is in the pools that fish tend to favor, or in the spawning areas they use.

An hourly time profile of DO levels at a sampling site is a valuable set of data, because it shows the change in DO levels from the low point (just before sunrise) to the high point (sometime near midday). However, this might not be practical for a volunteer monitoring program. Note the time of your DO sampling to help judge when in the daily cycle the data were collected.

DO is measured either in milligrams per liter of percent saturation. Milligrams per liter are the amount or oxygen in a liter of water. Percent saturation is the amount of oxygen in a liter of water relative to the total amount of oxygen that the water can hold at that temperature.

DO samples are collected using a special BOD bottle: a glass bottle with a turtleneck and a ground stopper. You can fill the bottle directly in the stream if the stream can be waded in or boated in, or you can use a sampler dropped from a bridge or boat into water deep enough to submerse it. Samplers can be made or purchased.

14.4.5.2 Dissolved Oxygen Test Methods

DO is measured primarily either by using some variation of the Winkler method, or by using a meter and probe.

14.4.5.2.1 Winkler Method (Azide Modification)

The Winkler method (azide modification) involves filling a sample bottle completely with water (no air is left to bias the test). The DO is then fixed using a series of reagents that form a titrated acid compound. Titration involves the drop-by-drop addition of a reagent that neutralizes the acid compound, causing a change in the color of the solution. The point at which the color changes is the end point and is equivalent to the amount of oxygen dissolved in the sample. The sample is usually fixed and titrated in the field at the sample site. Preparing the sample in the field and delivering it to a lab for titration is possible.

The azide modification method is best suited for relatively clean waters; otherwise, substances such as color, organics, suspended solids, sulfide, chlorine, and ferrous and ferric iron can interfere with test results. If fresh azide is used, nitrite will not interfere with the test.

In testing, iodine is released in proportion to the amount of DO present in the sample. By using sodium

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thiosulfate with starch as the indicator, the sample can be titrated to determine the amount of DO present.

The chemicals used include

1. Manganese sulfate solution
2. Alkaline azide-iodide solution
3. Sulfuric acid (concentrated)
4. Starch indicator
5. Sodium thiosulfate solution 0.025 N, phenylarsine solution 0.025 N, or potassium biniodate solution 0.025 N
6. Distilled or deionized water

The equipment used includes:

1. Buret (graduated to 0.1 mL)
2. Buret stand
3. 300 mL BOD bottles
4. 500 mL Erlenmeyer flasks
5. 1.0 mL pipets with elongated tips
6. Pipet bulb
7. 250 mL graduated cylinder
8. Laboratory-grade water rinse bottle
9. Magnetic stirrer and stir bars (optional)

14.4.5.2.1.1 Procedure

The procedure for the Winkler method includes the following:

1. Collect sample in a 300 mL BOD bottle.
2. Add 1 mL manganous sulfate solution at the surface of the liquid.
3. Add 1 mL alkaline-iodide-azide solution at the surface of the liquid.
4. Stopper the bottle and mix by inverting the bottle.
5. Allow the floc to settle halfway in the bottle, remix, and allow to settle again.
6. Add 1 mL concentrated sulfuric acid at the surface of the liquid.
7. Restopper the bottle, rinse top with laboratory-grade water, and mix until precipitate is dissolved.
8. The liquid in the bottle should appear clear and have an amber color.
9. Measure 201 mL from the BOD bottle into an Erlenmeyer flask.
10. Titrate with 0.025 N PAO or thiosulfate to a pale yellow color. Note the amount of titrant.
11. Add 1 mL of starch indicator solution.
12. Titrate until blue color first disappears.
13. Record total amount of titrant.

14.4.5.2.1.2 Calculation

To calculate the DO concentration when the modified Winkler titration method is used:

$$\mathrm{DO}\ (\mathrm{mg/L}) = \frac{\left[\mathrm{Buret}_{\mathrm{Final}}\ (\mathrm{mL}) - \mathrm{Buret}_{\mathrm{Start}}\ (\mathrm{mL})\right] \times \mathrm{N} \times 8000}{\mathrm{Sample\ Volume}\ (\mathrm{mL})} \quad (14.1)$$

Note: Using a 200-mL sample and a 0.025 N (N = Normality of the solution used to titrate the sample) titrant reduces this calculation to:

$$\mathrm{DO}\ (\mathrm{mg/L}) = \mathrm{mL\ Titrant\ Used}$$

EXAMPLE 14.1

Problem:

The operator titrates a 200-mL DO sample. The buret reading at the start of the titration was 0.0 mL. At the end of the titration, the buret read 7.1 mL. The concentration of the titrating solution was 0.025 N. What is the DO concentration in milligrams per liter?

Solution:

$$\mathrm{DO}\ (\mathrm{mg/L}) = \frac{[7.1\ \mathrm{mL} - 0.0\ \mathrm{mL}] \times 0.025 \times 8000}{200\ \mathrm{mL}}$$

$$= 7.1\ \mathrm{mg/L}$$

DO field kits using the Winkler method are relatively inexpensive, especially compared to a meter and probe. Field kits run between $35 and $200, and each kit comes with enough reagents to run 50 to 100 DO tests. Replacement reagents are inexpensive, and you can buy them already measured out for each test in plastic pillows.

You can also purchase the reagents in larger quantities in bottles, and measure them out with a volumetric scoop. The pillows' advantage is that they have a longer shelf life and are much less prone to contamination or spillage. Buying larger quantities in bottles has the advantage of considerably lower cost per test.

The major factor in the expense for the kits is the method of titration used: — eyedropper-type or syringe-type titrator. Eyedropper-type or syringe-type titration is less precise than digital titration, because a larger drop of titrant is allowed to pass through the dropper opening, and on a microscale, the drop size (and thus volume of titrant) can vary from drip to drop. A digital Titrator or a buret (a long glass tube with a tapered tip like a pipette) permits much more precision and uniformity for titrant it allows to pass.

If a high degree of accuracy and precision in DO results is required, a digital titrator should be used. A kit that uses an eyedropper-type or syringe-type titrator is suitable for most other purposes. The lower cost of this type of DO field kit might be attractive if several teams

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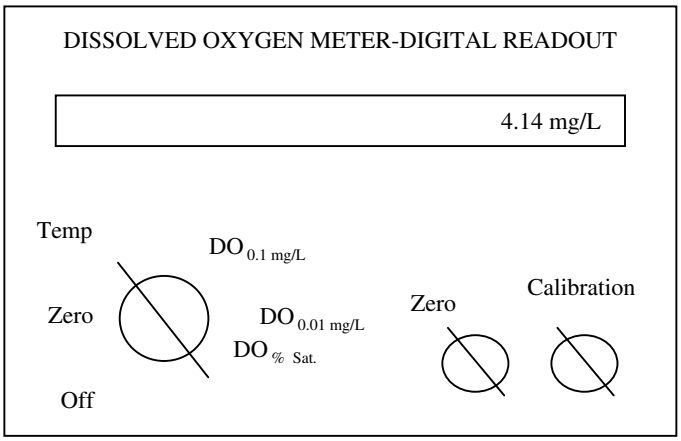

FIGURE 14.13 Dissolved oxygen meter. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

of samplers and testers at multiple sites at the same time are used.

14.4.5.2.2 Meter and Probe

A DO meter is an electronic device that converts signals from a probe placed in the water into units of DO in milligrams per liter. Most meters and probes also measure temperature. The probe is filled with a salt solution and has a selectively permeable membrane that allows DO to pass from the stream water into the salt solution. The DO that has diffused into the salt solution changes the electric potential of the salt solution. This change is sent by electric cable to the meter, converting the signal to milligrams per liter on a scale that the user can read.

14.4.5.2.2.1 Methodology

If samples are to be collected for analysis in the laboratory, a special APHA sampler or the equivalent must be used. This is the case because if the sample is exposed or mixed with air during collection, test results can change dramatically. Therefore, the sampling device must allow collection of a sample that is not mixed with atmospheric air and allows for at least 3 times-bottle overflow (see Figure 14.12).

Again, because the DO level in a sample can change quickly, only grab samples that should be used for DO testing. Samples must be tested immediately (within 15 min) after collection.

Note: Samples collected for analysis using the modified Winkler titration method may be preserved for up to 8 h by adding 0.7 mL of concentrated sulfuric acid or by adding all the chemicals required by the procedure. Samples collected from the aeration tank of the activated sludge process must be preserved using a solution of copper sulfate-sulfamic acid to inhibit biological activity.

The advantage of using the DO oxygen meter method is that the meter can be used to determine DO concentration directly (see Figure 14.13). In the field, a direct reading can be obtained using a probe (see Figure 14.14) or by collection of samples for testing in the laboratory using a laboratory probe (see Figure 14.15).

Note: The field probe can be used for laboratory work by placing a stirrer in the bottom of the sample bottle, but the laboratory probe should never be used in any situation where the entire probe might be submerged.

The probe used in the determination of DO consists of two electrodes, a membrane, and a membrane filling solution. Oxygen passes through the membrane into the filling solution and causes a change in the electrical current passing between the two electrodes. The change is measured and displayed as the concentration of DO. In order to be accurate, the probe membrane must be in proper operating condition, and the meter must be calibrated before use.

The only chemical used in the DO meter method during normal operation is the electrode filling solution. However, in the Winkler DO method, chemicals are required for meter calibration.

Calibration prior to use is important. Both the meter and the probe must be calibrated to ensure accurate results. The frequency of calibration is dependent on the frequency of use. For example, if the meter is used once a day, then calibration should be performed before use. There are three methods available for calibration: saturated water, saturated air, and the Winkler method. It is important to note that if the Winkler method is not used for routine calibration method, periodic checks using this method are recommended.

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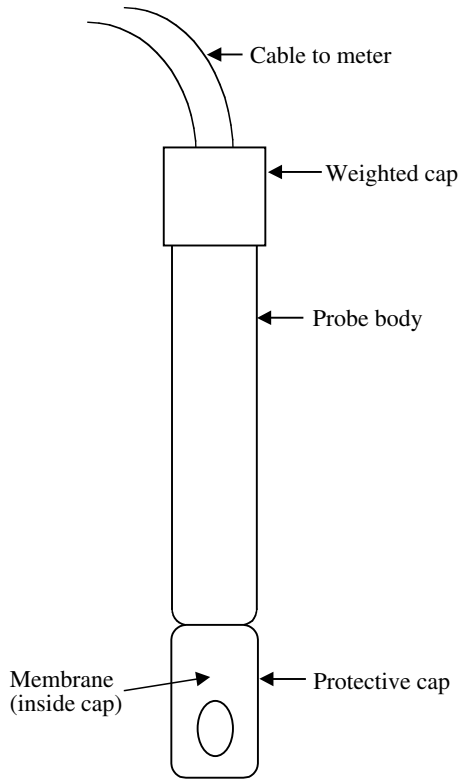

FIGURE 14.14 Dissolved oxygen-field probe. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

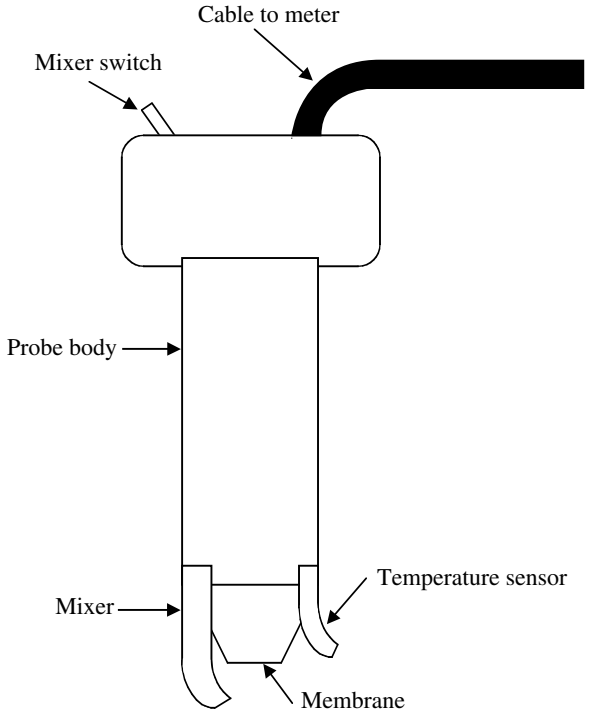

FIGURE 14.15 Dissolved oxygen-lab probe. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.4.5.2.2.2 Procedure

It is important to keep in mind that the meter and probe manufacturer's operating procedures should always be followed. Normally, the manufacturer's recommended procedure will include the following generalized steps:

1. Turn DO meter on, and allow 15 min for it to warm up.
2. Turn meter switch to zero, and adjust as needed.
3. Calibrate meter using the saturated air, saturated water, or Winkler azide procedure for calibration.
4. Collect sample in 300 mL bottle, or place field electrode directly in stream.
5. Place laboratory electrode in BOD bottle without trapping air against membrane, and turn on stirrer.
6. Turn meter switch to temperature setting, and measure temperature.
7. Turn meter switch to DO mode, and allow 10 sec for meter reading to stabilize.
8. Read DO in milligrams per liter from meter, and record the results.

No calculation is necessary using this method because results are read directly from the meter.

DO meters are expensive compared to field kits that use the titration method. Meter or probe combinations run between $500 and $1200, including a long cable to connect the probe to the meter. The advantage of a meter or probe is that DO and temperature can be quickly read at any point where the probe is inserted into the stream. DO levels can be measured at a certain point on a continuous basis. The results are read directly as milligrams per liter, unlike the titration methods, in which the final titration result might have to be converted by an equation to milligrams per liter.

DO meters are more fragile than field kits, and repairs to a damaged meter can be costly. The meter or probe must be carefully maintained. It must also be calibrated before each sample run, and if many tests are done, between sampling. Because of the expense, a small water or wastewater facility might only have one meter or probe, which means that only one team of samplers can sample DO and must test all the sites. With field kits, several teams can sample simultaneously.

14.4.6 Biochemical Oxygen Demand Testing

As mentioned, BOD measures the amount of oxygen consumed by microorganisms in decomposing organic matter in stream water. BOD also measures the chemical oxidation of inorganic matter (the extraction of oxygen from water via chemical reaction). A test is used to measure the amount of oxygen consumed by these organisms during a specified period of time (usually 5 d at 20ºC). The rate

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of oxygen consumption in a stream is affected by a number of variables: temperature, pH, the presence of certain kinds of microorganisms, and the type of organic and inorganic material in the water.

BOD directly affects the amount of DO in water bodies. The greater the BOD, the more rapidly oxygen is depleted in the water body, leaving less oxygen available to higher forms of aquatic life. The consequences of high BOD are the same as those for low DO: aquatic organisms become stressed, suffocate, and die. Most river waters used as water supplies have a BOD less than 7 mg/L, making dilution unnecessary.

Sources of BOD include leaves and wood debris; dead plants and animals; animal manure; effluents from pulp and paper mills, wastewater treatment plants, feedlots, and food-processing plants; failing septic systems; and urban stormwater runoff.

Note: To evaluate raw water's potential for use as a drinking water supply, it is usually sampled, analyzed, and tested for BOD when turbid, polluted water is the only source available.

14.4.6.1 Sampling Considerations

BOD is affected by the same factors that affect DO. Aeration of stream water (e.g., by rapids and waterfalls) will accelerate the decomposition of organic and inorganic material. Therefore, BOD levels at a sampling site with slower, deeper waters might be higher for a given column of organic and inorganic material that the levels for a similar site in high aerated waters.

Chlorine can also affect BOD measurement by inhibiting or killing the microorganisms that decompose the organic and inorganic matter in a sample. If sampling in chlorinated waters (such as those below the effluent from a sewage treatment plant), neutralizing the chlorine with sodium thiosulfate is necessary (see *Standard Methods).*

BOD measurement requires taking two samples at each site. One is tested immediately for DO, and the second is incubated in the dark at 20ºC for 5 d and tested for remaining DO. The difference in oxygen levels between the first test and the second test (in milligrams per liter) is the amount of BOD. This represents the amount of oxygen consumed by microorganisms and used to break down the organic matter present in the sample bottle during the incubation period. Because of the 5-d incubation, the tests are conducted in a laboratory.

Sometimes by the end of the 5-d incubation period, the DO level is zero. This is especially true for rivers and streams with a lot of organic pollution. Since knowing when the zero point was reached is not possible, determining the BOD level is also impossible. In this case, diluting the original sample by a factor that results in a final DO level of at least 2 mg/L is necessary. Special dilution water should be used for the dilutions (see *Standard Methods).*

Some experimentation is needed to determine the appropriate dilution factor for a particular sampling site. The result is the difference in DO between the first measurement and the second, after multiplying the second result by the dilution factor. *Standard Methods* prescribes all phases of procedures and calculations for BOD determination. A BOD test is not required for monitoring water supplies.

14.4.6.2 BOD Sampling, Analysis, and Testing

The approved biochemical oxygen demand sampling and analysis procedure measures the DO depletion (biological oxidation of organic matter in the sample) over a 5-day period under controlled conditions (20ºC in the dark). The test is performed using a specified incubation time and temperature. Test results are used to determine plant loadings, plant efficiency, and compliance with NPDES effluent limitations. The duration of the test (5 days) makes it difficult to use the data effectively for process control.

The standard BOD test does not differentiate between oxygen used to oxidize organic matter and oxygen used to oxidize organic and ammonia nitrogen to more stable forms. Because many biological treatment plants now control treatment processes to achieve oxidation of the nitrogen compounds, there is a possibility that BOD test results for plant effluent and some process samples may produce BOD test results based on both carbon and nitrogen oxidation. To avoid this situation, a nitrification inhibitor can be added. When this is done, the test results are known as carbonaceous BOD (CBOD). A second uninhibited BOD should also be run whenever CBOD is determined.

When taking a BOD sample, no special sampling container is required. Either a grab or composite sample can be used. BOD_5 samples can be preserved by refrigeration at or below 4ºC (not frozen) — composite samples must be refrigerated during collection. Maximum holding time for preserved samples is 48 h.

Using the incubation of dissolved approved test method, a sample is mixed with dilution water in several different concentrations (dilutions). The dilution water contains nutrients and materials to provide optimum environment. The chemicals used are DO, ferric chloride, magnesium sulfate, calcium chloride, phosphate buffer, and ammonium chloride.

Note: Remember all chemicals can be dangerous if not used properly and in accordance with the recommended procedures. Review appropriate sections of the individual chemical materials safety data sheet to determine proper methods for handling and for safety precautions that should be taken.

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TABLE 14.8
BOD_5 Test Procedure

1. Fill two bottles with BOD dilution water. Insert stoppers.
2. Place sample in two BOD bottles. Fill with dilution water. Insert stoppers.
3. Test for DO.
4. Incubate for 5 d.
5. Test for DO.
6. Add 1 mL $MnSO_4$ below surface.
7. Add 1 mL alkaline Kl below surface.
8. Add 1 mL H_2SO_4.
9. Transfer 203 mL to flask.
10. Titrate with polyalphaolefin or thiosulfate.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Sometimes it is necessary to add (seed) healthy organisms to the sample. The DO of the dilution and the dilution water is determined. If seed material is used, a series of dilutions of seed material must also be prepared. The dilutions and dilution blanks are incubated in the dark for 5 days at 20ºC ± 1ºC. At the end of 5 d, the DO of each dilution and the dilution blanks are determined.

For the test results to be valid, certain criteria must be achieved. These test criteria are listed as follows:

1. Dilution water blank DO change must be ≤0.2 mg/L.
2. Initial DO must be >7.0 mg/L, but ≤9.0 mg/L (or saturation at 20ºC and test elevation).
3. Sample dilution DO depletion must be ≥2.0 mg/L.
4. Sample dilution residual DO must be ≥1.0 mg/L.
5. Sample dilution initial DO must be ≥7.0 mg/L.
6. Seed correction should be ≥0.6, but ≤1.0 mg/L.

The BOD_5 test procedure consists of 10 steps (for unchlorinated water) as shown in Table 14.8.

Note: BOD_5 is calculated individually for all sample dilutions that meet the criteria. Reported result is the average of the BOD_5 of each valid sample dilution.

14.4.6.2.1 BOD_5 Calculation (Unseeded)

Unlike the direct reading instrument used in the DO analysis, BOD results require calculation. There are several criteria used in selecting which BOD_5 dilutions should be used for calculating test results. Consult a laboratory testing reference manual (such as *Standard Methods*) for this information.

At the present time, there are two basic calculations for BOD_5. The first is used for samples that have not been seeded. The second must be used whenever BOD_5 samples are seeded. In this section, we illustrate the calculation procedure for unseeded samples:

$$BOD_5\ (\text{Unseeded}) = \frac{\left[DO_{Start}\ (mg/L) - DO_{Final}\ (mg/L)\right] \times 300\ mL}{\text{Sample Volume (mL)}} \quad (14.2)$$

EXAMPLE 14.2

Problem:

The BOD_5 test is completed. Bottle 1 of the test had a DO of 7.1 mg/L at the start of the test. After 5 d, bottle 1 had a DO of 2.9 mg/L. Bottle 1 contained 120 mg/L of sample. Determine the BOD_5

Solution:

$$BOD_5\ (\text{Unseeded}) = \frac{[7.1\ mg/L - 2.9\ mg/L] \times 300\ mL}{120\ mL}$$

$$= 10.5\ mg/L$$

14.4.6.2.2 BOD_5 Calculation (Seeded)

If the BOD_5 sample has been exposed to conditions that could reduce the number of healthy, active organisms, the sample must be seeded with organisms. Seeding requires use of a correction factor to remove the BOD_5 contribution of the seed material:

$$\text{Seed Correction} = \frac{\text{Seed Material } BOD_5 \times \text{Seed in Dilution (mL)}}{300\ mL} \quad (14.3)$$

$$BOD_5\ (\text{Seeded}) = \frac{\left[\left(DO_{Start}[mg/L] - DO_{Final}[mg/L]\right) - \text{Seed Correction}\right] \times 300}{\text{Sample Volume (mL)}} \quad (14.4)$$

EXAMPLE 14.3

Problem:

Using the data provided below, determine the BOD_5:

BOD_5 of Seed Material		**90 mg/L**
Dilution #1	mL of seed material	3 mL
	mL of sample	100 mL
	Start DO	7.6 mg/L
	Final DO	2.7 mg/L

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Solution:

$$\text{Seed Correction} = \frac{90\ \text{mg/L} \times 3\ \text{mL}}{300\ \text{mL}}$$

$$= 0.90\ \text{mg/L}$$

$$\text{BOD}_5\ (\text{Seeded}) = \frac{\left[\left(7.6\ \text{mg/L} - 2.7\ \text{mg/L}\right) - 0.90\right] \times 300}{100\ \text{mL}}$$

$$= 12\ \text{mg/L}$$

14.4.7 Temperature Measurement

As mentioned, an ideal water supply should have, at all times, an almost constant temperature or one with minimum variation. Knowing the temperature of the water supply is important because the rates of biological and chemical processes depend on it.

Temperature affects the oxygen content of the water (oxygen levels become lower as temperature increases); the rate of photosynthesis by aquatic plants; the metabolic rates of aquatic organisms; and the sensitivity of organisms to toxic wastes, parasites, and diseases.

Causes of temperature change include weather; removal of shading streambank vegetation, impoundments (a body of water confined by a barrier, such as a dam); and discharge of cooling water, urban stormwater, and groundwater inflows to the steam.

14.4.7.1 Sampling and Equipment Considerations

Temperature, for example, in a stream, varies with width and depth; the temperature of well-sunned portions of a stream can be significantly higher than the shaded portion of the water on a sunny day. In a small stream, the temperature will be relatively constant as long as the stream is uniformly in sun or shade. In a large stream, temperature can vary considerably with width and depth, regardless of shade. If safe to do so, temperature measurements should be collected at varying depths and across the surface of the stream to obtain vertical and horizontal temperature profiles. This can be done at each site at least once to determine the necessity of collecting a profile during each sampling visit. Temperature should be measured at the same place every time.

Temperature is measured in the stream with a thermometer or a meter. Alcohol-filled thermometers are preferred over mercury-filled because they are less hazardous if broken. Armored thermometers for field use can withstand more abuse than unprotected glass thermometers and are worth the additional expense. Meters for other tests (e.g., pH [acidity] or DO) also measure temperature and can be used instead of a thermometer.

14.4.8 Hardness Measurement

As mentioned, hardness refers primarily to the amount of calcium and magnesium in the water. Calcium and magnesium enter water mainly by leaching of rocks. Calcium is an important component of aquatic plant cell walls and the shells and bones of many aquatic organisms. Magnesium is an essential nutrient for plants and is a component of the chlorophyll molecule.

Hardness test kits express test results in parts per million of $CaCO_3$, but these results can be converted directly to calcium or magnesium concentrations:

$$\text{Calcium Hardness as ppm } CaCO_3 \times 0.40 = \text{ppm Ca} \quad (14.5)$$

$$\text{Magnesium Hardness as ppm } CaCO_3 \times 0.24 = \text{ppm Mg} \quad (14.6)$$

Note: Because of less contact with soil minerals and more contact with rain, surface raw water is usually softer than groundwater.

As a rule, when hardness is greater than 150 mg/L, softening treatment may be required for public water systems. Hardness determination via testing is required to ensure efficiency of treatment.

14.4.8.1 Measuring Hardness

(Note: Keep in mind that when measuring calcium hardness, the concentration of calcium is routinely measured separately from total hardness. Its concentration in waters can range from 0 to several thousand mg/L, as $CaCO_3$. Likewise, when measuring magnesium hardness, magnesium is routinely determined by subtracting calcium hardness from total harness. There is usually less magnesium than calcium in natural water. Lime dosage for water softening operation is partly based on the concentration of magnesium hardness in the water.)

In the hardness test, the sample must be carefully measured. A buffer is then added to the sample to correct pH for the test and an indicator to signal the titration end point.

The indicator reagent is normally blue in a sample of pure water, but if calcium or magnesium ions are present in the sample, the indicator combines with them to form a red-colored complex. The titrant in this test is ethylenediaminetetraacetic acid (EDTA; used with its salts in the titration method), a chelant that actually pulls the calcium and magnesium ions away from a red-colored complex. The EDTA is added dropwise to the sample until all the calcium and magnesium ions have been chelated away from the complex and the indicator returns to its normal blue color. The amount of EDTA required to cause the color change is a direct indication of the amount of calcium and magnesium ions in the sample.

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Some hardness kits include an additional indicator that is specific for calcium. This type of kit will provide three readings: total hardness, calcium hardness, and magnesium hardness. For interference, precision, and accuracy, consult the latest edition of *Standard Methods.*

14.4.9 pH Measurement

pH is defined as the negative log of the hydrogen ion concentration of the solution. This is a measure of the ionized hydrogen in solution. Simply, it is the relative acidity or basicity of the solution. The chemical and physical properties and the reactivity of almost every component in water are dependent upon pH. It relates to corrosivity, contaminant solubility, and the water's conductance. It has a secondary maximum contaminant level (MCL) range set at 6.5 to 8.5.

14.4.9.1 Analytical and Equipment Considerations

The pH can be analyzed in the field or in the lab. If analyzed in the lab, it must be measured within 2 h of the sample collection. This is because the pH will change from the carbon dioxide from the air as it dissolves in the water, bringing the pH toward 7.

If your program requires a high degree of accuracy and precision in pH results, the pH should be measured with a laboratory quality pH meter and electrode. Meters of this quality range in cost from around $250 to $1000. Color comparators and pH pocket pals are suitable for most other purposes. The cost of either of these is in the $50 range. The lower cost of the alternatives might be attractive if multiple samplers are used to sample several sites at the same time.

14.4.9.2 pH Meters

A pH meter measures the electric potential (millivolts) across an electrode when immersed in water. This electric potential is a function of the hydrogen ion activity in the sample; therefore, pH meters can display results in either millivolts or pH units.

A pH meter consists of a potentiometer, which measures electric potential where it meets the water sample; a reference electrode, which provides a constant electric potential; and a temperature compensating device, which adjusts the readings according to the temperature of the sample (since pH varies with temperature). The reference and glass electrodes are frequently combined into a single probe called a combination electrode.

A wide variety of meters are available, but the most important part of the pH meter is the electrode. Purchasing a good, reliable electrode and following the manufacturer's instructions for proper maintenance is important. Infrequently used or improperly maintained electrodes are subject to corrosion, which makes them highly inaccurate.

14.4.9.3 pH Pocket Pals and Color Comparators

pH pocket pals are electronic handheld pens that are dipped in the water, providing a digital readout of the pH. They can be calibrated to only one pH buffer. (Lab meters can be calibrated to two or more buffer solutions and are more accurate over a wide range of pH measurements.)

Color comparators involve adding a reagent to the sample that colors the sample water. The intensity of the color is proportional to the pH of the sample, then matched against a standard color chart. The color chart equates particular colors to associated pH values that can be determined by matching the colors from the chart to the color of the sample.

For instructions on how to collect and analyze samples, refer to *Standard Methods.*

14.4.10 Turbidity Measurement

As previously described, turbidity is a measure of water clarity — how much the material suspended in water decreases the passage of light through the water. Turbidity consists of suspended particles in the water and may be caused by a number of materials, organic and inorganic. These particles are typically in the size range of 0.004 (clay) to 1.0 mm (sand). The occurrence of turbid source waters may be permanent or temporary. It can affect the color of the water.

Higher turbidity increases water temperatures because suspended particles absorb more heat. This reduces the concentration of DO because warm water holds less DO than cold. Higher turbidity also reduces the amount of light penetrating the water, which reduces photosynthesis and the production of DO. Suspended materials can clog fish gills, reducing resistance to disease in fish, lowering growth rates, and affecting egg and larval development. As the particles settle, they can blanket the stream bottom (especially in slower waters) and smother fish eggs and benthic macroinvertebrates

Turbidity also affects treatment plant operations. For example, turbidity hinders disinfection by shielding microbes, some of them pathogens, from the disinfectant. Obviously, this is the most important significance of turbidity monitoring; the test for it is an indication of the effectiveness of the filtration of water supplies. It is important to note that turbidity removal is the principal reason for chemical addition, settling, coagulation, settling, and filtration in potable water treatment. Sources of turbidity include:

1. Soil erosion
2. Waste discharge
3. Urban runoff
4. Eroding stream banks

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5. Large numbers of bottom feeders (e.g., carp) that stir up bottom sediments
6. Excessive algal growth

14.4.10.1 Sampling and Equipment Considerations

Turbidity can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activity, discharges, and other sources. Turbidity often increases sharply during rainfall, especially in developed watersheds that typically have relatively high proportions of impervious surfaces. The flow of stormwater runoff from impervious surfaces rapidly increases stream velocity, increasing the erosion rates of streambanks and channels. Turbidity can also rise sharply during dry weather if Earth-disturbing activities occur in or near a stream without erosion control practices in place.

Regular monitoring of turbidity can help detect trends that might indicate increasing erosion in developing watersheds. However, turbidity is closely related to stream flow and velocity and should be correlated with these factors. Comparisons of the change in turbidity over time, therefore, should be made at the same point at the same flow.

Keep in mind that turbidity is not a measurement of the amount of suspended solids present or the rate of sedimentation of a stream; it measures only the amount of light that is scattered by suspended particles. Measurement of total solids is a more direct measurement of the amount of material suspended and dissolved in water.

Turbidity is generally measured by using a turbidity meter or turbidimeter. The turbidimeter is a modern nephelometer. (Originally, this was a box containing a light bulb that directed light at a sample. The amount of light scattered at right angles by the turbidity particles was measured, as a measure of the turbidity in the sample, and registered as nephelometric turbidity units [NTUs].) The turbidimeter uses a photoelectric cell to register the scattered light on an analog or digital scale, and the instrument is calibrated with permanent turbidity standards composed of the colloidal substance, formazin. Meters can measure turbidity over a wide range — from 0 to 1000 NTUs. A clear mountain stream might have a turbidity of around 1 NTU, whereas a large river like the Mississippi might have a dry-weather turbidity of 10 NTUs. Because these values can jump into hundreds of NTUs during runoff events, the turbidity meter to be used should be reliable over the range in which you will be working. Meters of this quality cost about $800. Many meters in this price range are designed for field or lab use.

An operator may also take samples to a lab for analysis. Another approach, discussed previously, is to measure transparency (an integrated measure of light scattering and absorption) instead of turbidity. Water clarity or transparency can be measured using a Secchi disk (see Figure 14.11) or transparency tube. The Secchi disk can only be used in deep, slow moving rivers; the transparency tube (a comparatively new development) is gaining acceptance in and around the country, but is not widely used.

14.4.10.2 Using a Secchi Disk

A Secchi disk is a black and white disk that is lowered by hand into the water to the depth at which it vanishes from sight (see Figure 14.11). The distance to vanishing is then recorded — the clearer the water, the greater the distance. Secchi disks are simple to use and inexpensive. For river monitoring they have limited use because in most cases the river bottom will be visible and the disk will not reach a vanishing point. Deeper, slower moving rivers are the most appropriate places for Secchi disk measurement. However, the current might require that the disk be extra-weighted so it does not sway and make measurement difficult. Secchi disks cost about $50, but can be homemade.

The line attached to the Secchi disk must be marked in waterproof ink according to units designated by the sampling program. Many programs require samplers to measure to the nearest 1/10 m. Meter intervals can be tagged (e.g., with duct tape) for ease of use.

To measure water clarity with a Secchi disk:

1. Check to make sure that the Secchi disk is securely attached to the measured line.
2. Lean over the side of the boat and lower the Secchi disk into the water, keeping your back to the sun to block glare.
3. Lower the disk until it disappears from view. Lower it 1/3 m and then slowly raise the disk until it just reappears. Move the disk up and down until you find the exact vanishing point.
4. Attach a clothespin to the line at the point where the line enters the water. Record the measurement on your data sheet. Repeating the measurement provides you with a quality control check.

The key to consistent results is to train samplers to follow standard sampling procedures. If possible, have the same individual take the reading at the same site throughout the season.

14.4.10.3 Transparency Tube

Pioneered by Australia's department of conservation, the transparency tube is a clear, narrow plastic tube marked in units with a dark pattern painted on the bottom. Water is poured into the tube until the pattern disappears. Some U.S. volunteer monitoring programs (e.g., the Tennessee Valley Authority [TVA] Clean Water Initiative and the Minnesota Pollution Control Agency [MPCA]) are testing the transparency tube in streams and rivers. MPCA uses tubes marked in centimeters. It has found tube readings to

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be related fairly well to lab measurements of turbidity and total suspended solids (TSS), but does not recommend the transparency tube for applications where precise and accurate measurement is required or in highly colored waters.

The TVA and MPCA recommended the following sampling considerations:

1. Collect the sample in a bottle or bucket in midstream and at middepth if possible. Avoid stagnant water and sample as far from the shoreline as is safe. Avoid collecting sediment from the bottom of the stream.
2. Face upstream as you fill the bottle or bucket.
3. Take readings in open but shaded conditions. Avoid direct sunlight by turning your back to the sun.
4. Carefully stir or swish the water in the bucket or bottle until it is homogeneous, taking care not a produce air bubbles (these scatter light and affect the measurement). Pour the water slowly in the tube while looking down the tube. Measure the depth of the water column in the tube at the point where the symbol just disappears.

14.4.11 Orthophosphate Measurement

Earlier we discussed the nutrients phosphorus and nitrogen. Both phosphorus and nitrogen are essential nutrients for the plants and animals that make up the aquatic food web. Because phosphorus is the nutrient in short supply in most freshwater systems, even a modest increase in phosphorus can (under the right conditions) set off a whole chain of undesirable events in a stream. These events include accelerated plant growth; algae blooms; low DO; and the death of certain fish, invertebrates, and other aquatic animals.

Phosphorus comes from many sources, both natural and human. These include soil and rocks, wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage areas, disturbed land areas, drained wetlands, water treatment, and commercial cleaning preparations.

14.4.11.1 Forms of Phosphorus

Phosphorus has a complicated story. Pure, elemental phosphorus (P) is rare. In nature, phosphorus usually exists as part as part of a phosphate molecule (PO4). Phosphorus in aquatic systems occurs as organic phosphate and inorganic phosphate. Organic phosphate consists of a phosphate molecule associated with a carbon-based molecule, as in plant or animal tissue. Phosphate that is not associated with organic material is inorganic, the form required by plants. Animals can use either organic or inorganic phosphate.

Both organic and inorganic phosphate can either be dissolved in the water or suspended (attached to particles in the water column).

14.4.11.2 The Phosphorus Cycle

Recall that phosphorus cycles through the environment, changing form as it does so (see Figure 11.19). Aquatic plants take in dissolved inorganic phosphorus, as it becomes part of their tissues. Animals get the organic phosphorus they need by eating either aquatic plants, other animals, or decomposing plant and animal material.

In water bodies, as plants and animals excrete wastes or die, the organic phosphorus they contain sinks to the bottom, where bacterial decomposition converts it back to inorganic phosphorus, both dissolved and attached to particles. This inorganic phosphorus gets back into the water column when animals, human activity, interactions, or water currents stir up the bottom. Then plants take it up and the cycle begins again.

In a stream system, the phosphorus cycle tends to move phosphorus downstream as the current carries decomposing plant and animal tissue and dissolved phosphorus. It becomes stationary only when it is taken up by plants or is bound to particles that settle to the bottom of ponds.

In the field of water quality chemistry, phosphorus is described by several terms. Some of these terms are chemistry based (referring to chemically based compounds), and others are methods based (they describe what is measured by a particular method).

The term orthophosphate is a chemistry-based term that refers to the phosphate molecule all by itself. More specifically, orthophosphate is simple phosphate or reactive phosphate (i.e., Na3PO4), sodium phosphate (tribasic), NaH2PO4, and sodium phosphate (monobasic). Orthophosphate is the only form of phosphate that can be directly tested for in the laboratory; it is the form that bacteria use directly for metabolic processes. Reactive phosphorus is a corresponding method-based term that describes what is actually being measured when the test for orthophosphate is being performed. Because the lab procedure is not quite perfect, mostly orthophosphate is obtained along with a small fraction of some other forms.

More complex inorganic phosphate compounds are referred to as condensed phosphates or polyphosphates. The method-based term for these forms is acid hydrolyzable.

14.4.11.3 Testing Phosphorus

Testing phosphorus is challenging because it involves measuring very low concentrations, down to 0.01 mg/L or even lower. Even such very low concentrations of phosphorus can have a dramatic impact on streams. Less sensitive methods should be used only to identify serious problem areas.

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While many tests for phosphorus exist, only four are likely to be performed by most samplers:

1. The total orthophosphate test is largely a measure of orthophosphate. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate. The EPA-approved method for measuring is known as the ascorbic acid method. Briefly, a reagent (either liquid or powder) containing ascorbic acid and ammonium molybdate reacts with orthophosphate in the sample to form a blue compound. The intensity of the blue color is directly proportional to the amount of orthophosphate in the water.
2. The total phosphate test measures all the forms of phosphorus in the sample (orthophosphate, condensed phosphate, and organic phosphate). It first digests (heating and acidifying) the sample to convert all the other forms to orthophosphate, and the orthophosphate is then measured by the ascorbic acid method. Because the sample is not filtered, the procedure measures both dissolved and suspended orthophosphate.
3. The dissolved phosphorus test measures that fraction of the total phosphorus that is in solution in the water (as opposed to being attached to suspended particles). It is determined by filtering the sample and analyzing the filtered sample for total phosphorus.
4. Insoluble phosphorus is calculated by subtracting the dissolved phosphorus result from the total phosphorus result.

All these tests have one thing in common — they all depend on measuring orthophosphate. The total orthophosphate test measures the orthophosphate that is already present in the sample. The others measure that which is already present and that which is formed when the other forms of phosphorus are converted to orthophosphate by digestion.

Monitoring phosphorus involves two basic steps:

1. Collecting a water sample
2. Analyzing it in the field or lab for one of the types of phosphorus described above

14.4.11.4 Sampling and Equipment Considerations

Sample containers made of either some form of plastic or Pyrex® glass are acceptable to EPA. Phosphorus molecules have a tendency to absorb (attach) to the inside surface of sample containers. Therefore, if containers are to be reused, they must be acid-washed to remove absorbed phosphorus. The container must be able to withstand repeated contact with hydrochloric acid. Plastic containers, either high-density polyethylene or polypropylene, might be preferable to glass from a practical standpoint because they are better able to withstand breakage. Some programs use disposable, sterile, plastic Whirl-pak bags. The size of the container depends on the sample amount needed for the phosphorus analysis method chosen, and the amount needed for other analyses to be performed.

All containers that will hold water samples or come into contact with reagents used in the orthophosphate test must be dedicated. They should not be used for other tests, eliminating the possibility that reagents containing phosphorus will contaminate the labware. All labware should be acid-washed.

The only form of phosphorus this text recommends for field analysis is total orthophosphate, which uses the ascorbic acid method on an untreated sample. Analysis of any of the other forms requires adding potentially hazardous reagents, heating the sample to boiling, and using too much time and too much equipment to be practical. In addition, analysis for other forms of phosphorus is prone to errors and inaccuracies in field situations. Pretreatment and analysis for these other forms should be handled in a laboratory.

14.4.11.5 Ascorbic Acid Method for Determining Orthophosphate

In the ascorbic acid method, a combined liquid or prepackaged powder reagent consisting of sulfuric acid, potassium antimonyl tartrate, ammonium molybdate, and ascorbic acid (or comparable compounds) is added to either 50 or 25 mL of the water sample. This colors the sample blue in direct proportion to the amount of orthophosphate in the sample. Absorbance or transmittance is then measured after 10 minutes, but before 30 minutes. It is measured by using a color comparator with a scale in milligrams per liter that increases with the increase in color hue, or an electronic meter that measures the amount of light absorbed or transmitted at a wavelength of 700 to 880 nm (depending on manufacturer's directions).

A color comparator may be useful for identifying heavily polluted sites with high concentrations (greater than 0.1 mg/L). However, matching the color of a treated sample to a comparator can be very subjective, especially at low concentrations, and lead to variable results.

A field spectrophotometer or colorimeter with a 2.5-cm light path and an infrared photocell (set for a wavelength of 700 to 880 nm) is recommended for accurate determination of low concentrations (between 0.2 and 0.02 mg/L). Using a meter requires that a prepared known standard concentration be analyzed ahead of time to convert the absorbence readings of a stream sample to milligrams per liter, or that the meter reads directly in milligrams per liter.

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For information on how to prepare standard concentrations and on how to collect and analyze samples, refer to *Standard Methods* and EPA's *Methods for Chemical Analysis of Water and Wastes*, 2nd ed., 1991, Method 365.2.

14.4.12 Nitrates Measurement

As mentioned, nitrates are a form of nitrogen found in several different forms in terrestrial and aquatic ecosystems. These forms of nitrogen include ammonia (NH3), nitrates (NO3), and nitrites (NO2). Nitrates are essential plant nutrients, but excess amounts can cause significant water quality problems. Together with phosphorus, nitrates in excess amounts can accelerate eutrophication, causing dramatic increases in aquatic plant growth and changes in the types of plants and animals that live in the stream. This affects DO, temperature, and other indicators. Excess nitrates can cause hypoxia (low levels of DO) and can become toxic to warm-blooded animals at higher concentrations (10 mg/L or higher) under certain conditions. The natural level of ammonia or nitrate in surface water is typically low (less than 1 mg/L); in the effluent of wastewater treatment plants, it can range up to 30 mg/L. Conventional potable water treatment plants cannot remove nitrate. High concentrations must be prevented by controlling the input at the source.

Sources of nitrates include wastewater treatment plants, runoff from fertilized lawns and cropland, failing on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors.

14.4.12.1 Sampling and Equipment Considerations

Nitrates from land sources end up in rivers and streams more quickly than other nutrients like phosphorus. This is because they dissolve in water more readily than phosphorus, which has an attraction for soil particles. As a result, nitrates serve as a better indicator of the possibility of a source of sewage or manure pollution during dry weather.

Water that is polluted with nitrogen-rich organic matter might show low nitrates. Decomposition of the organic matter lowers the DO level, which slows the rate at which ammonia is oxidized to nitrite (NO2) and then to nitrate (NO3). Under such circumstances, monitoring for nitrites or ammonia (considerably more toxic to aquatic life than nitrate) might be also necessary. (See *Standard Methods* Section 4500-NH3 and Section 4500-NH2 for appropriate nitrite methods.)

Water samples to be tested for nitrate should be collected in glass or polyethylene containers that have been prepared by using Method B (see Section 14.3.4.2).

Two methods are typically used for nitrate testing: the cadmium reduction method and the nitrate electrode. The more commonly used cadmium reduction method produces a color reaction measured either by comparison to a color wheel or by use of a spectrophotometer. A few programs also use a nitrate electrode, which can measure in the range of 0 to 100-mg/L nitrate. A newer colorimetric immunoassay technique for nitrate screening is also now available.

14.4.12.2 Cadmium Reduction Method

In the cadmium reduction method, nitrate is reduced to nitrite by passing the sample through a column packed with activated cadmium. The sample is then measured quantitatively for nitrite.

More specifically, the cadmium reduction method is a colorimetric method that involves contact of the nitrate in the sample with cadmium particles, which cause nitrates to be converted to nitrites. The nitrites then react with another reagent to form a red color, in proportional intensity to the original amount of nitrate. The color is measured either by comparison to a color wheel with a scale in milligrams per liter that increases with the increase in color hue, or by use of an electronic spectrophotometer that measures the amount of light absorbed by the treated sample at a 543-nm wavelength. The absorbence value converts to the equivalent concentration of nitrate against a standard curve. Methods for making standard solutions and standard curves are presented in *Standard Methods.*

The sampling or monitoring supervisor before each sampling run should create this curve. The curve is developed by making a set of standard concentrations of nitrate, reacting them, developing the corresponding color, and plotting the absorbence value for each concentration against concentration. A standard curve could also be generated for the color wheel. Use of the color wheel is appropriate only if nitrate concentrations are greater than 1 mg/L. For concentrations below 1 mg/L, use a spectrophotometer. Matching the color of a treated sample at low concentrations to a color wheel (or cubes) can be very subjective and can lead to variable results. Color comparators can, however, be effectively used to identify sites with high nitrates.

This method requires that the samples being treated are clear. If a sample is turbid, filter it through a 0.45-μm filter. Be sure to test to make sure the filter is nitrate-free. If copper, iron, or others metals are present in concentrations above several milligrams per liter, the reaction with the cadmium will slow down and the reaction time must be increased.

The reagents used for this method are often prepackaged for different ranges, depending on the expected concentration of nitrate in the stream. For example, the Hack company provides reagents for the following ranges: low

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(0 to 0.40 mg/L), medium (0 to 15 mg/L), and high (0 to 30 mg/L). Determining the appropriate range for the stream being monitored is important.

14.4.12.3 Nitrate Electrode Method

A nitrate electrode (used with a meter) is similar in function to a DO meter. It consists of a probe with a sensor that measures nitrate activity in the water; this activity affects the electric potential of a solution in the probe. This change is then transmitted to the meter, which converts the electric signal to a scale that is read in millivolts. The millivolts are then converted to milligrams per liter of nitrate by plotting them against a standard curve. The accuracy of the electrode can be affected by high concentrations of chloride or bicarbonate ions in the sample water. Fluctuating pH levels can also affect the meter reading.

Nitrate electrodes and meters are expensive compared to field kits that employ the cadmium reduction method. (The expense is comparable if a spectrophotometer is used rather than a color wheel.) Meter or probe combinations run between $700 and $1200, including a long cable to connect the probe to the meter. If the program has a pH meter that displays readings in millivolts, it can be used with a nitrate probe and no separate nitrate meter is needed. Results are read directly as milligrams per liter.

Although nitrate electrodes and spectrophotometers can be used in the field, they have certain disadvantages. These devices are more fragile than the color comparators and are more at risk of breaking in the field. They must be carefully maintained and must be calibrated before each sample run; if many tests are being run they must be calibrated between samplings. This means that samples are best tested in the lab. Note that samples to be tested with a nitrate electrode should be at room temperature, whereas color comparators can be used in the field with samples at any temperature.

14.4.13 Solids Measurement

Solids in water are defined as any matter that remains as residue upon evaporation and drying at 103°C. They are separated into two classes: suspended solids and dissolved solids:

$$\text{Total Solids} = \text{Suspended Solids (nonfilterable residue)} + \text{Dissolved Solids (filterable residue)}$$

As shown above, total solids are dissolved solids plus suspended and settleable solids in water. In natural freshwater bodies, dissolved solids consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions — particles that will pass through a filter with pores of around 2 µm (0.002 cm) in size. Suspended solids include silt and clay particles, plankton, algae, fine organic debris, and other particulate matter. These are particles that will not pass through a 2-µm filter.

The concentration of total dissolved solids affects the water balance in the cells of aquatic organisms. An organism placed in water with a very low level of solids (e.g., distilled water) swells because water tends to move into its cells, which have a higher concentration of solids. An organism placed in water with a high concentration of solids shrinks somewhat because the water in its cells tends to move out. This in turn affects the organism's ability to maintain the proper cell density, making keeping its position in the water column difficult. It might float up or sink down to a depth to which it is not adapted, and it might not survive.

Higher concentrations of suspended solids can serve as carriers of toxics, which readily cling to suspended particles. This is particularly a concern where pesticides are being used on irrigated crops. Where solids are high, pesticide concentrations may increase well beyond those of the original application as the irrigation water travels down irrigation ditches. Higher levels of solids can also clog irrigation devices; they might become so high that irrigated plant roots will lose water rather than gain it.

A high concentration of total solids will make drinking water unpalatable, and might have an adverse effect on people who are not used to drinking such water. Levels of total solids that are too high or too low can also reduce the efficiency of wastewater treatment plants, as well as the operation of industrial processes that use raw water.

Total solids affect water clarity. Higher solids decrease the passage of light through water, slowing photosynthesis by aquatic plants. Water heats up more rapidly and holds more heat; this might adversely affect aquatic life adapted to a lower temperature regime.

Sources of total solids include industrial discharges, sewage, fertilizers, road runoff, and soil erosion. Total solids are measured in milligrams per liter.

14.4.13.1 Solids Sampling and Equipment Considerations

When conducting solids testing, there are many things that affect the accuracy of the test or result in wide variations in results for a single sample. These include the following:

1. Drying temperature
2. Length of drying time
3. Condition of desiccator and desiccant
4. Nonrepresentative samples' lack of consistency in test procedure
5. Failure to achieve constant weight prior to calculating results

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There are several precautions that can help to increase the reliability of test results:

1. Use extreme care when measuring samples, weighing materials, and drying or cooling samples.
2. Check and regulate oven and furnace temperatures frequently to maintain the desired range.
3. Use an indicator drying agent in the desiccator that changes color when it is no longer good. Change or regenerate the desiccant when necessary.
4. Keep desiccator cover greased with the appropriate type of grease. This will seal the desiccator and prevent moisture from entering the desiccator as the test glassware cools.
5. Check ceramic glassware for cracks and glass fiber filter for possible holes. A hole in a glass filter will cause solids to pass through and give inaccurate results.
6. Follow manufacturer's recommendation for care and operation of analytical balances.

Total solids are important to measure in areas where discharges from sewage treatment plants, industrial plants, or extensive crop irrigation may occur. In particular, streams and rivers in arid regions where water is scarce and evaporation is high tend to have higher concentrations of solids, and are more readily affected by human introduction of solids from land use activities.

Total solids measurements can be useful as an indicator of the effects of runoff from construction, agricultural practices, logging activities, sewage treatment plant discharges, and other sources. As with turbidity, concentrations often increase sharply during rainfall, especially in developed watersheds. They can also rise sharply during dry weather if earth-disturbing activities occur in or near the stream without erosion control practices in place. Regular monitoring of total solids can help detect trends that might indicate increasing erosion in developing watersheds. Total solids are closely related to stream flow and velocity, and should be correlated with these factors. Any change in total solids over time should be measured at the same site at the same flow.

Total solids are measured by weighing the amount of solids present in a known volume of sample; this is accomplished by weighing a beaker, filling it with a known volume, evaporating the water in an oven and completely drying the residue, and weighing the beaker with the residue. The total solids concentration is equal to the difference between the weight of the beaker with the residue and the weight of the beaker without it. Since the residue is so light in weight, the lab needs a balance that is sensitive to weights in the range of 0.0001 g. Balances of this type are called analytical or Mettler balances and are expensive (around $3000). The technique requires that the beakers be kept in a desiccator, a sealed glass container that contains material that absorbs moisture and ensures that the weighing is not biased by water condensation on the beaker. Some desiccants change color to indicate moisture content.

The measurement of total solids cannot be done in the field. Samples must be collected using clean glass or plastic bottles or Whirl-pak bags and taken to a laboratory where the test can be run.

14.4.13.2 Total Suspended Solids

As mentioned, the term solids means any material suspended or dissolved in water and wastewater. Although normal domestic wastewater contains a very small amount of solids (usually less than 0.1%), most treatment processes are designed specifically to remove or convert solids to a form that can be removed or discharged without causing environmental harm.

In sampling for TSS, samples may be either grab or composite and can be collected in either glass or plastic containers. TSS samples can be preserved by refrigeration at or below 4ºC (not frozen). However, composite samples must be refrigerated during collection. The maximum holding time for preserved samples is 7 d.

14.4.13.2.1 Test Procedure

In short, to conduct a TSS test procedure, a well-mixed measured sample is poured into a filtration apparatus and, with the aid of a vacuum pump or aspirator, is drawn through a preweighted glass fiber filter. After filtration, the glass filter is dried at 103 to 105ºC, cooled and reweighed. The increase in weight of the filter and solids compared to the filter alone represents the TSS.

An example of the specific test procedure used for TSS is given below.

1. Select a sample volume that will yield between 10 and 200 mg of residue with a filtration time of 10 min or less.

Note: If filtration time exceeds 10 min, increase filter area or decrease volume to reduce filtration time.

Note: For nonhomogenous samples or samples with very high solids concentrations (e.g., raw wastewater or mixed liquor), use a larger filter to ensure a representative sample volume can be filtered.

2. Place preweighed glass fiber filter on filtration assembly in a filter flask.
3. Mix sample well, and measure the selected volume of sample.
4. Apply suction to filter flask. Wet filter with a small amount of laboratory-grade water to seal it.

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5. Pour the selected sample volume into filtration apparatus.
6. Draw sample through filter.
7. Rinse measuring device into filtration apparatus with three successive 10 mL portions of laboratory-grade water. Allow complete drainage between rinsings.
8. Continue suction for 3 min after filtration of final rinse is completed.
9. Remove the glass filter from the filtration assembly (membrane filter funnel or clean Gooch crucible). If using the large disks and membrane filter assembly, transfer the glass filter to a support (aluminum pan or evaporating dish) for drying.
10. Place the glass filter with solids and support (pan, dish, or crucible) in a drying oven.
11. Dry filter and solids to constant weight at 103 to 105ºC (at least 1 h).
12. Cool to room temperature in a desiccator.
13. Weigh the filter. Support and record the constant weight in test record.

14.4.13.2.2 TSS Calculations

To determine the total suspended solids concentration in milligrams per liter, we use the following equations:

1. To determine weight of dry solids in grams:

$$\text{Dry Solids (g)} = \text{Wt. of Dry Solids and Filter, g} - \text{Wt. of Dry Filter (g)} \tag{14.7}$$

2. To determine weight of dry solids in milligrams:

$$\text{Dry Solids (mg)} = \text{Wt. of Solids and Filter, g} - \text{Wt. of Dry Filter (g)} \tag{14.8}$$

3. To determine the TSS concentration in milligrams per liter;

$$\text{TSS (mg/L)} = \frac{\text{Dry Solids (mg)} \times 1000 \text{ ml/L}}{\text{ml Sample}} \tag{14.9}$$

EXAMPLE 14.4

Problem:

Using the data provided below, calculate TSS:

Sample Volume (mL)	250 mL
Weight of Dry Solids and Filter (g)	2.305 g
Weight of Dry Filter (g)	2.297 g

Solution:

Dry Solids (g) = 2.305 g – 2.297 g = 0.008 g
Dry Solids (mg) = 0.008 g × 1000 mg/g = 8 mg

$$\text{TSS (mg/L)} = \frac{8.0 \times 1000 \text{ mL/L}}{250 \text{ mL}} = 32.0 \text{ mg/L}$$

14.4.13.3 Volatile Suspended Solids Testing

When the total suspended solids are ignited at 550 ± 50ºC, the volatile (organic) suspended solids of the sample are converted to water vapor and carbon dioxide and are released to the atmosphere. The solids that remain after the ignition (ash) are the inorganic or fixed solids.

In addition to the equipment and supplies required for the TSS test, you need the following:

1. Muffle furnace (550 ± 50ºC)
2. Ceramic dishes
3. Furnace tongs
4. Insulated gloves

14.4.13.3.1 Test Procedure

An example of the test procedure used for volatile suspended solids is given below:

1. Place the weighed filter with solids and support from the TSS test in the muffle furnace.
2. Ignite filter, solids, and support at 550 ± 50ºC for 15 to 20 min.
3. Remove the ignited solids, filter, and support from the furnace, and partially air cool.
4. Cool to room temperature in a desiccator.
5. Weigh ignited solids, filter, and support on an analytical balance.
6. Record the weight of ignited solids, filter, and support.

14.4.13.3.2 Total Volatile Suspended Solids Calculations

Calculating total volatile suspended solids (TVSS) requires the following information:

1. Weights of dry solids, filter, and support in grams
2. Weight of ignited solids, filter and support in grams

$$\text{TVSS (mg/L)} = \frac{(A - C) \times 1000 \text{ mg/g} \times 1000 \text{ mL/L}}{\text{Sample Volume (mL)}} \tag{14.10}$$

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where

A = Weight of dried solids, filter, and support
C = Weight of ignited solids, filter, and support

Example 14.5

Problem:

Given:

A = 1.6530 g
C = 1.6330 g
Sample volume = 100

Calculate the TVSS.

Solution:

$$\text{TVSS}\ (\text{mg/L}) = \frac{(1.6530\ \text{g} - 1.6330\ \text{g}) \times 1000\ \text{mg/g} \times 1000\ \text{mL/L}}{100\ \text{mL}} = \frac{0.02 \times 1{,}000{,}000\ \text{mg/L}}{100} = 200\ \text{mg/L}$$

Note: Total fixed suspended solids (TFSS) is the difference between the TVSS and the TSS concentrations:

$$\text{TFSS}\ (\text{mg/L}) = \text{TSS} - \text{TVSS} \tag{14.11}$$

Example 14.6

Problem:

Given:

TSS = 202 mg/L
TVSS = 200 mg/L

Calculate TFSS.

Solution:

$$\text{TFSS}\ (\text{mg/L}) = 202\ \text{mg/L} - 200\ \text{mg/L} = 2\ \text{mg/L}$$

14.4.14 Conductivity Testing

Conductivity is a measure of the capacity of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge), or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity.

Conductivity in streams and rivers is affected primarily by the geology of the area through which the water flows. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is composed of more inert materials that do not ionize (dissolve into ionic components) when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity because of the presence of materials that ionize when washed into the water. Groundwater inflows can have the same effects, depending on the bedrock they flow through.

Discharges to streams can change the conductivity depending on their makeup. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate; an oil spill would lower conductivity.

The basic unit of measurement of conductivity is the mho or siemens. Conductivity is measured in micromhos per centimeter or microsiemens per centimeter. Distilled water has conductivity in the range of 0.5 to 3 μmhos/cm. The conductivity of rivers in the U.S. generally ranges from 50 to 1500 μmhos/cm. Studies of inland freshwaters indicated that streams supporting good mixed fisheries have a range between 150 and 500 μmhos/cm. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. Industrial waters can range as high as 10,000 μmhos/cm.

14.4.14.1 Sampling, Testing, and Equipment Considerations

Conductivity is useful as a general measure of source water quality. Each stream tends to have a relatively constant range of conductivity that, once established, can be used as a baseline for comparison with regular conductivity measurements. Significant changes in conductivity could indicate that a discharge or some other source of pollution has entered a stream.

The conductivity test is not routine in potable water treatment, but when performed on source water is a good indicator of contamination. Conductivity readings can also be used to indicate wastewater contamination or saltwater intrusion.

Note: Distilled water used for potable water analyses at public water supply facilities must have a conductivity of no more than 1 μmho/cm.

Conductivity is measured with a probe and a meter. Voltage is applied between two electrodes in a probe immersed in the sample water. The drop of voltage caused

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by the resistance of the water is used to calculate the conductivity per centimeter. The meter converts the probe measurement to micromhos per centimeter and displays the result for the user.

Note: Some conductivity meters can also be used to test for total dissolved solids and salinity. The total dissolved solids concentration in milligrams per liter (mg/L) can also be calculated by multiplying the conductivity result by a factor between 0.55 and 0.9, which is empirically determined (see *Standard Methods* #2510).

Suitable conductivity meters cost about $350. Meters in this price range should also measure temperature and automatically compensate for temperature in the conductivity reading. Conductivity can be measured in the field or the lab. In most cases, collecting samples in the field and taking them to a lab for testing is probably better. In this way, several teams can collect samples simultaneously. If testing in the field is important, meters designed for field use can be obtained for around the same cost mentioned above.

If samples will be collected in the field for later measurement, the sample bottle should be a glass or polyethylene bottle that has been washed in phosphate-free detergent and rinsed thoroughly with both tap and distilled water. Factory-prepared Whirl-pak bags may be used.

14.4.15 Total Alkalinity

As mentioned, alkalinity is defined as the ability of water to resist a change in pH when acid is added; it relates to the pH buffering capacity of the water. Almost all natural waters have some alkalinity. These alkaline compounds in the water, such as bicarbonates (baking soda is one type), carbonates, and hydroxides, remove H^+ ions and lower the acidity of the water (which means increased pH). They usually do this by combining with the H^+ ions to make new compounds. Without this acid-neutralizing capacity, any acid added to a stream would cause an immediate change in the pH. Measuring alkalinity is important in determining a stream's ability to neutralize acidic pollution from rainfall or wastewater — one of the best measures of the sensitivity of the stream to acid inputs.

Alkalinity in streams is influenced by rocks and soils, salts, certain plant activities, and certain industrial wastewater discharges.

Total alkalinity is determined by measuring the amount of acid (e.g., sulfuric acid) needed to bring the sample to a pH of 4.2. At this pH all the alkaline compounds in the sample are completely used up. The result is reported as milligrams per liter of calcium carbonate (mg/L $CaCO_3$).

Alkalinity is important in water treatment plant operations. For example, testing for alkalinity in potable water treatment is most important for its relation to coagulant addition; it is important that there exists enough natural alkalinity in the water to buffer chemical acid addition so that floc formation will be optimum, and the turbidity removal can proceed. In water softening, proper chemical dosage will depend on the type and amount of alkalinity in the water. For corrosion control, the presence of adequate alkalinity in a water supply neutralizes any acid tendencies, and prevents it from becoming corrosive.

14.4.15.1 Analytical and Equipment Considerations

For total alkalinity, a double end point titration using a pH meter (or pH pocket pal) and a digital titrator or buret is recommended. This can be done in the field or in the lab. If alkalinity must be analyzed in the field, a digital titrator should be used instead of a buret, because burets are fragile and more difficult to set up. The alkalinity method described below was developed by the Acid Rain Monitoring Project of the University of Massachusetts Water Resources Research Center (from River Watch Network, *Total Alkalinity and pH Field and Laboratory Procedures*, July 1992).

14.4.15.2 Burets, Titrators, and Digital Titrators for Measuring Alkalinity

The total alkalinity analysis involves titration. In this test, titration is the addition of small, precise quantities of sulfuric acid (the reagent) to the sample, until the sample reaches a certain pH (known as an end point). The amount of acid used corresponds to the total alkalinity of the sample. Alkalinity can be measured using a buret, titrator, or digital titrator (described below):

1. A buret is a long, graduated glass tube with a tapered tip like a pipette and a valve that opens to allow the reagent to drop out of the tube. The amount of reagent used is calculated by subtracting the original volume in the buret from the column left after the end point has been reached. Alkalinity is calculated based on the amount used.
2. Titrators forcefully expel the reagent by using a manual or mechanical plunger. The amount of reagent used is calculated by subtracting the original volume in the titrator from the volume left after the end point has been reached. Alkalinity is then calculated based on the amount used or is read directly from the titrator.
3. Digital titrators have counters that display numbers. A plunger is forced into a cartridge containing the reagent by turning a knob on the titrator. As the knob turns, the counter changes

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in proportion to the amount of reagent used. Alkalinity is then calculated based on the amount used. Digital titrators cost approximately $100.

Digital titrators and burets allow for much more precision and uniformity in the amount of titrant that is used.

14.4.16 Fecal Coliform Bacteria Testing

(Note: Much of the information in this section is from EPA's *Test Methods for* Escherichia coli and *Enterococci in Water by the Membrane Filter Procedure* (Method #1103.1), EPA 600/4–85–076, 1985; and *Bacteriological Ambient Water Quality Criteria for Marine and Fresh Recreational Waters*, EPA 440/5–84–002, Office of Research and Development, Cincinnati, OH, 1986.)

Fecal coliform bacteria are nondisease-causing organisms that are found in the intestinal tract of all warm blooded animals. Each discharge of body wastes contains large amounts of these organisms. The presence of fecal coliform bacteria in a stream or lake indicates the presence of human or animal wastes. The number of fecal coliform bacteria present is a good indicator of the amount of pollution present in the water.

EPA's Total Coliform Rule, (816-F-01–035, Nov. 2001) specifies the following:

1. The purpose of the Total Coliform Rule is to improve public health protection by reducing fecal pathogens to minimal levels through control of total coliform bacteria, including fecal coliforms and *Escherichia coli* (*E. coli*).
2. The Total Coliform Rule Establishes an MCL based on the presence or absence of total coliforms, modifies monitoring requirements including testing for fecal coliforms or *E. coli,* requires use of a sample siting plan, and also requires sanitary surveys for systems collecting fewer than five samples per month.
3. The Total Coliform Rule applies to all public water systems.
4. Implementation of the Total Coliform Rule has resulted in reduction in risk of illness from disease causing organisms associated with sewage or animal wastes. Disease symptoms may include diarrhea, cramps, nausea, and possibly jaundice, and associated headaches and fatigue.

14.4.16.1 Fecal Coliforms: General Information

As mentioned, fecal coliforms are used as indicators of possible sewage contamination because they are commonly found in human and animal feces. Although they are not generally harmful, they indicate the possible presence of pathogenic (disease-causing) bacteria, and protozoa that also live in human and animal digestive systems. Their presence in streams suggests that pathogenic microorganisms might also be present, and that swimming in or eating shellfish from the waters might present a health risk. Since testing directly for the presence of a large variety of pathogens is difficult, time-consuming, and expensive, water is usually tested for coliforms and fecal streptococci instead. Sources of fecal contamination to surface waters include wastewater treatment plants, on-site septic systems, domestic and wild animal manure, and storm runoff.

In addition to the possible health risks associated with the presence of elevated levels of fecal bacteria, they can also cause cloudy water, unpleasant odors, and an increased oxygen demand.

Note: In addition to the most commonly tested fecal bacteria indicators, total coliforms, fecal coliforms, and *E. coli*, fecal streptococci and enterococci are also commonly used as bacteria indicators. The focus of this presentation is on total coliforms and fecal coliforms.

14.4.16.2 Fecal Coliforms

Fecal coliforms are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood, and in other places outside the human body. The usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test, because their presence indicates contamination of a water supply by an outside source.

Fecal coliforms, a subset of total coliform bacteria, are more fecal-specific in origin. However, even this group contains a genus, Klebsiella, with species that are not necessarily fecal in origin. Klebsiella are commonly associated with textile and pulp and paper mill wastes. If these sources discharge to a local stream, consideration should be given to monitoring more fecal and human-specific bacteria. For recreational waters, this group was the primary bacteria indicator until relatively recently, when EPA began recommending *E. coli* and enterococci as better indicators of health risk from water contact. Fecal coliforms are still being used in many states as indicator bacteria.

14.4.16.3 Sampling Requirements

Under EPA's *Total Coliform Rule*, sampling requirements are specified as follows:

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14.4.16.3.1 Routine Sampling Requirements

1. Total coliform samples must be collected at sites that are representative of water quality throughout the distribution system according to a written sample siting plan subject to state review and revision.
2. Samples must be collected at regular time intervals throughout the month. Groundwater systems serving 4900 persons or fewer may collect them on the same day.
3. Monthly sampling requirements are based on population served (see Table 14.9 for the minimum sampling frequency).
4. A reduced monitoring frequency may be available for systems serving 1000 persons or fewer and using only groundwater. This is only if a sanitary survey within the past 5 years shows the system is free of sanitary defects (the frequency may be no less than 1 sample/quarter for community and 1 sample/year for non-community systems).
5. Each total coliform-positive routine sample must be tested for the presence of fecal coliforms or *E. coli*.

14.4.16.3.2 Repeat Sampling Requirements

1. Within 24 h of learning of a total coliform-positive ROUTINE sample result, at least 3 REPEAT samples must be collected and analyzed for total coliforms.
2. One REPEAT sample must be collected from the same tap as the original sample.
3. One REPEAT sample must be collected within five service connections upstream.
4. One REPEAT sample must be collected within five service connections downstream.
5. Systems that collect one ROUTINE sample per month or fewer must collect a fourth REPEAT sample.
6. If any REPEAT sample is total coliform-positive:
7. The system must analyze that total coliform-positive culture for fecal coliforms or *E. coli*.
8. The system must collect another set of REPEAT samples, as before, unless the MCL has been violated and the system has notified the state.

14.4.16.3.3 Additional Routine Sample Requirements

A positive ROUTINE or REPEAT total coliform result requires a minimum of five ROUTINE samples be collected the following month the system provides water to the public unless waived by the state.

TABLE 14.9
Public Water System ROUTINE Monitoring Frequencies

Population	Minimum Samples/Month
25–1,000[a]	1
1001–2500	2
2501–3300	3
3301–4100	4
4101–4900	5
4901–5800	6
5801–6700	7
6701–7600	8
7601–8500	9
8501–12,900	10
12,901–17,200	15
17,201–21,500	20
21,501–25,000	25
25,001–33,000	30
33,001–41,000	40
41,001–50,000	50
50,001–59,000	60
59,001–70,000	70
70,000–83,000	80
83,001–96,000	90
96,001–130,000	100
130,000–220,000	120
220,001–320,000	150
320,001–450,000	180
450,001–600,000	210
600,001–780,000	240
780,001–970,000	270
970,001–1,230,000	330
1,520,001–1,850,000	360
1,850,001–2,270,000	390
2,270,001–3,020,000	420
3,020,001–3,960,000	450
≥3,960,001	480

[a] Includes public water systems that have at least 15 service connections, but serve < 25 people.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.4.16.3.4 Other Total Coliform Rule Provisions

1. Systems collecting fewer than 5 ROUTINE samples per month must have a sanitary survey every 5 years (or every 10 years if it is a non-community water system using protected and disinfected groundwater).
2. Systems using surface water or groundwater under the direct influence of surface water and meeting filtration avoidance criteria must col-

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lect and have analyzed one coliform sample each day the turbidity of the source water exceeds 1 NTU. This sample must be collected from a tap near the first service connection.

14.4.16.3.5 Compliance

Compliance is based on the presence or absence of total coliforms. Compliance is also determined each calendar month the system serves water to the public (or each calendar month that sampling occurs for systems on reduced monitoring). The results of ROUTINE and REPEAT samples are used to calculate compliance.

In regards to violations, a monthly MCL violation is triggered if a system collecting fewer than 40 samples per month has greater than 1 ROUTINE/REPEAT sample per month that is total coliform-positive. In addition, a system collecting at least 40 samples per month has greater than 5.0% of the ROUTINE/REPEAT samples in a month that is total coliform-positive is technically in violation of the Total Coliform Rule. An acute MCL violation is triggered if any public water system has any fecal coliform- or *E. coli*-positive REPEAT sample or has a fecal coliform- or *E. coli*-positive ROUTINE sample followed by a total coliform-positive REPEAT sample.

The Total Coliform Rule also has requirements for public notification and reporting. For example, for a monthly MCL Violation, the violation must be reported to the state no later than the end of the next business day after the system learns of the violation. The public must be notified within 14 days. For an acute MCL violation, the violation must be reported to the state no later than the end of the next business day after the system learns of the violation. The public must be notified within 72 hours. Systems with ROUTINE or REPEAT samples that are fecal coliform- or *E. Coli*-positive must notify the state by the end of the day they are notified of the result or by the end of the next business day if the state office is already closed.

14.4.16.4 Sampling and Equipment Considerations

For many reasons, bacteria can be difficult to sample and analyze. These reasons include:

1. Natural bacteria levels in streams can vary significantly.
2. Bacteria conditions are strongly correlated with rainfall, making the comparison of wet and dry weather bacteria data a problem.
3. Many analytical methods have a low level of precision, yet can be quite complex to accomplish.
4. Absolutely sterile conditions are essential to maintain while collecting and handling samples.

The primary equipment decision to make when sampling for bacteria is what type and size of sample container you will use. Once you have made that decision, the same straightforward collection procedure is used, regardless of the type of bacteria being monitored.

When monitoring bacteria, it is critical that all containers and surfaces with which the sample will come into contact be sterile. Containers made of either some form of plastic or Pyrex glass are acceptable to EPA. However, if the containers are to be reused, they must be sturdy enough to survive sterilization using heat and pressure. The containers can be sterilized by using an autoclave, a machine that sterilizes with pressurized steam. If using an autoclave, the container material must be able to withstand high temperatures and pressure. Plastic containers, either high-density polyethylene or polypropylene, might be preferable to glass from a practical standpoint because they will better withstand breakage. In any case, be sure to check the manufacturer's specifications to see whether the container can withstand 15 minutes in an autoclave at a temperature of 121°C without melting. (Extreme caution is advised when working with an autoclave.) Disposable, sterile, plastic Whirl-pak bags are used by a number of programs. The size of the container depends on the sample amount needed for the bacteria analysis method you choose and the amount needed for other analyses.

The two basic methods for analyzing water samples for bacteria in common use are the multiple tube fermentation method and the membrane filtration (MF) method (described later).

Given the complexity of the analysis procedures and the equipment required, field analysis of bacteria is not recommended. Bacteria can either be analyzed by the volunteer at a well-equipped lab or sent to a state-certified lab for analysis. If you send a bacteria sample to a private lab, make sure that the lab is certified by the state for bacteria analysis. Consider state water quality labs, university and college labs, private labs, wastewater treatment plant labs, and hospitals. You might need to pay these labs for analysis.

On the other hand, if you have a modern lab with the proper equipment and properly trained technicians, the fecal coliform testing procedures described in the following section will be helpful. A note of caution: if you decide to analyze your samples in your own lab, be sure to carry out a quality assurance or quality control program.

14.4.16.5 Fecal Coliform Testing

The Code of Federal Regulations (CFR) cites two approved methods for the determination of fecal coliform in water: (1) the multiple tube fermentation or most probable number (MPN) procedure, and (2) the MF procedure.

Note: Because the MF procedure can yield low or highly variable results for chlorinated wastewa-

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ter, EPA requires verification of results using the MPN procedure to resolve any controversies. Do not attempt to perform the fecal coliform test using the summary information provided in this handbook. Refer to the appropriate reference cited in CFR for a complete discussion of these procedures.

14.4.16.5.1 Testing Preparations

The preparations for fecal coliform testing are described below:

14.4.16.5.1.1 Equipment and Techniques

Whenever microbiological testing of water samples is performed, certain general considerations and techniques will be required. Because these are basically the same for each test procedure, they are reviewed here prior to discussion of the two methods:

1. Reagents and media — All reagents and media utilized in performing microbiological tests on water samples must meet the standards specified in the reference cited in CFR.
2. Reagent grade water — Deionized water that is tested annually and found to be free of dissolved metals and bactericidal or inhibitory compounds is preferred for use in preparing culture media and test reagents, although distilled water may be used.
3. Chemicals — All chemicals used in fecal coliform monitoring must be American Chemical Society reagent grade or equivalent.
4. Media — To ensure uniformity in the test procedures, the use of dehydrated media is recommended. Sterilized, prepared media in sealed test tubes, ampoules, or dehydrated media pads are also acceptable for use in this test.
5. Glassware and Disposable Supplies — all glassware, equipment, and supplies used in microbiological testing should meet the standards specified in the references cited in CFR.

14.4.16.5.1.2 Preparation of Equipment and Chemicals

All glassware used for bacteriological testing must be thoroughly cleaned using a suitable detergent and hot water. The glassware should be rinsed with hot water to remove all traces of residual from the detergent and, finally, should be rinsed with distilled water. Laboratories should use a detergent certified to meet bacteriological standards or, at a minimum, rinse all glassware after washing with two tap water rinses followed by five distilled water rinses.

For sterilization of equipment, the hot air sterilizer or autoclave can be used. When using the hot air sterilizer, all equipment should be wrapped in high-quality (Kraft) paper or placed in containers prior to hot air sterilization. All glassware, except those in metal containers, should be sterilized for a minimum of 60 min at 170°C. Sterilization of glassware in metal containers should require a minimum of 2 h. Hot air sterilization cannot be used for liquids.

When using an autoclave, sample bottles, dilution water, culture media, and glassware may be sterilized by autoclaving at 121°C for 15 min.

14.4.16.5.1.3 Sterile Dilution Water Preparation

The dilution water used for making sample serial dilutions is prepared by adding 1.25 mL of stock buffer solution and 5.0 mL of magnesium chloride solution to 1000 mL of distilled or deionized water. The stock solutions of each chemical should be prepared as outlined in the reference cited by the CFR. The dilution water is then dispensed in sufficient quantities to produce 9 or 99 mL in each dilution bottle following sterilization. If the membrane filter procedure is used, additional 60- to 100-mL portions of dilution water should be prepared and sterilized to provide rinse water required by the procedure.

14.4.16.5.1.4 Serial Dilution Procedure

At times, the density of the organisms in a sample makes it difficult to accurately determine the actual number of organisms in the sample. When this occurs, the sample size may need to be reduced to as one millionth of a milliliter. In order to obtain such small volumes, a technique known as serial dilutions has been developed.

14.4.16.5.1.5 Bacteriological Sampling

To obtain valid test results that can be utilized in the evaluation of process efficiency of water quality, proper technique, equipment, and sample preservation are critical. These factors are especially critical in bacteriological sampling.

1. Sample dechlorination — When samples of chlorinated effluents are to be collected and tested, the sample must be dechlorinated. Prior to sterilization, place enough sodium thiosulfate solution (10%) in a clean sample container to produce a concentration of 100 mg/L in the sample (for a 120-mL sample bottle, 0.1 mL is usually sufficient). Sterilize the sample container as previously described.
2. Sample procedure:
   A. Keep the sample bottle unopened after sterilization until the sample is to be collected.
   B. Remove the bottle stopper and hood or cap as one unit. Do not touch or contaminate the cap or the neck of the bottle.
   C. Submerge the sample bottle in the water to be sampled.
   D. Fill the sample bottle approximately 3/4 full, but not less than 100 mL.
   E. Aseptically replace the stopper or cap on the bottle.

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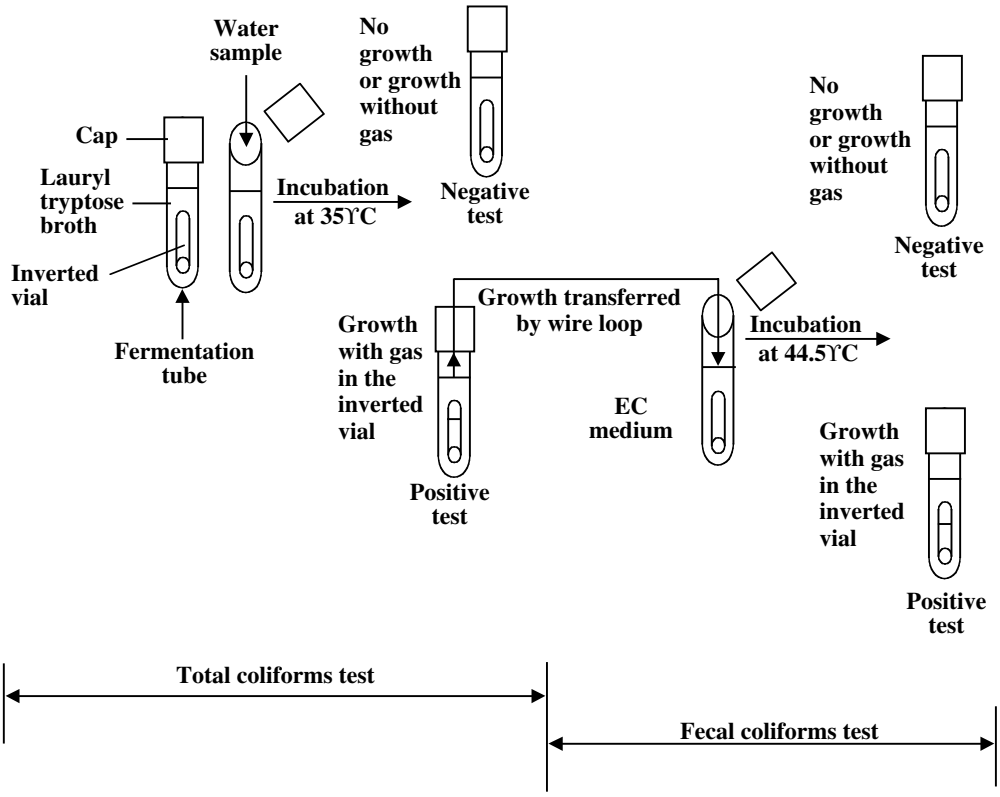

FIGURE 14.16 Diagram of the basic test for total coliforms and second-phase confirmatory test for thermotolerant fecal coliforms. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

F. Record the date, time, and location of sampling, as well as the sampler's name and any other descriptive information pertaining to the sample.

3. Sample preservation and storage — Examination of bacteriological water samples should be performed immediately after collection. If testing cannot be started within 1 h of sampling, the sample should be iced or refrigerated at 4°C or less. The maximum recommended holding time for fecal coliform samples from wastewater is 6 h. The storage temperature and holding time should be recorded as part of the test data.

14.4.16.5.2 Multiple Tube Fermentation Technique

The multiple fermentation technique for fecal coliform testing is useful in determining the fecal coliform density in most water, solid, or semisolid samples. Wastewater testing normally requires use of the presumptive and confirming test procedures. It is recognized as the method of choice for any samples that may be controversial (enforcement related). The technique is based on the MPN of bacteria present in a sample that produces gas in a series of fermentation tubes with various volumes of diluted sample. The MPN is obtained from charts based on statistical studies of known concentrations of bacteria.

The technique utilizes a two-step incubation procedure (see Figure 14.16). The sample dilutions are first incubated in lauryl (sulfonate) tryptose broth for 24 to 48 h (presumptive test). Positive samples are then transferred to EC broth and incubated for an additional 24 h (confirming test). Positive samples from this second incubation are used to statistically determine the MPN from the appropriate reference chart.

A single media, 24-hour procedure is also acceptable. In this procedure, sample dilutions are inoculated in A-1 media and are incubated for 3 h at 35°C then incubated the remaining 20 h at 44.5°C. Positive samples from these inoculations are then used to statistically determine the MPN value from the appropriate chart.

14.4.16.5.2.1 Fecal Coliform MPN Presumptive Test Procedure

The procedure for the fecal coliform MPN Presumptive test is described below:

1. Prepare dilutions and inoculate five fermentation tubes for each dilution.
2. Cap all tubes, and transfer to incubator.

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3. Incubate 24 + 2 hours at 35 ± 0.5°C.
4. Examine tubes for gas.
   A. Gas present = Positive test — transfer
   B. No gas = Continue incubation
5. Incubate total time 48 ± 3 hours at 35 ± 0.5°C.
6. Examine tubes for gas.
   A. Gas present = Positive test — transfer
   B. No gas = Negative test

Note: Keep in mind that the fecal coliform MPN confirming procedure of fecal coliform procedure using A-1 broth test is used to determine the MPN/100 mL. The MPN procedure for fecal coliform determinations requires a minimum of three dilutions with five tubes per dilution.

14.4.16.5.2.2 Calculation of MPN/100 mL

The calculation of the MPN test results requires selection of a valid series of three consecutive dilutions. The number of positive tubes in each of the three selected dilution inoculations is used to determine the MPN/100 mL. In selecting the dilution inoculations to be used in the calculation, each dilution is expressed as a ratio of positive tubes per tubes inoculated in the dilution (i.e.; three positive/five inoculated [3/5]). There are several rules to follow in determining the most valid series of dilutions. In the following examples, four dilutions were used for the test:

1. Using the confirming test data, select the highest dilution showing all positive results (no lower dilution showing less than all positive) and the next two higher dilutions.
2. If a series shows all negative values with the exception of one dilution, select the series that places the only positive dilution in the middle of the selected series.
3. If a series shows a positive result in a dilution higher than the selected series (using rule #1), it should be incorporated into the highest dilution of the selected series. After selecting the valid series, the MPN/1000 mL is determined by locating the selected series on the MPN reference chart. If the selected dilution series matches the dilution series of the reference chart, the MPN value from the chart is the reported value for the test. If the dilution series used for the test does not match the dilution series of the chart, the test result must be calculated.

$$\text{MPN/100 mL} = \text{MPN}_{\text{Chart}} \times \frac{\text{Sample Volume in 1}^{\text{st}}\text{ Dilution}_{\text{Chart}}}{\text{Sample Volume in 1}^{\text{st}}\text{ Dilution}_{\text{Sample}}} \tag{14.12}$$

EXAMPLE 14.7

Problem:

Using the results given below, calculate the MPN/100 mL.

Given:

Sample in each serial dilution (mL)	Positive Tubes (Inoculated)
10.0	5/5
1.0	5/5
0.1	3/5
0.01	1/5
0.001	1/5

Solution:

1. Select the highest dilution (tube with the lowest amount of sample) with all positive tubes (1.0-mL dilution). Select the next two higher dilutions (0.1 mL and 0.01 mL). In this case, the selected series will be 5–3–1.
2. Include any positive results in dilutions higher than the selected series (0.001 mL dilution 1/5). This changes the selected series to 5–3–2.
3. Using the first three columns of Table 14.10, locate this series (5–3–2).
4. Read the MPN value from the fourth column (140).
5. In Table 14.10, the dilution series begins with 10 mL. For this test, this series begins with 1.0 mL.

$$\text{MPN/100 mL} = 140\ \text{MPN/100 mL} \times \frac{10\ \text{mL}}{1\ \text{mL}}$$

$$= 1400\ \text{MPN/100 mL}$$

14.4.16.5.3 Membrane Filtration Technique

The membrane filtration technique can be useful for determining the fecal coliform density in wastewater effluents. Two exceptions to this technique are (1) primary treated wastewater that has not been chlorinated, and (2) wastewater that contains toxic metals or phenols. Chlorinated secondary or tertiary effluents may be tested using this method, but results are subject to verification by MPN technique.

The membrane filter technique utilizes a specially designed filter pad with uniformly sized pores (openings) that are small enough to prevent bacteria from entering the filter (see Figure 14.16). Another unique characteristic of the filter allows liquids, such as the media, placed under the filter to pass upward through the filter to provide nourishment required for bacterial growth.

Note: In the membrane filter method, the number of colonies grown estimates the number of coliforms.

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TABLE 14.10
MPN Reference Chart

Sample Volume (mL)				Sample Volume (mL)			
10	1.0	0.1	MPN/100 mL	10	1.0	0.1	MPN/100 mL
0	0	0	0	4	2	0	22
0	0	1	2	4	2	1	26
0	1	0	2	4	3	0	27
0	2	0	4	4	3	1	33
				4	4	0	34
1	0	0	2				
1	0	1	4	5	0	0	23
1	1	0	4	5	0	1	31
1	1	1	6	5	0	2	43
1	2	0	6	5	1	0	33
				5	1	1	46
2	0	0	5	5	1	2	63
2	0	1	7				
2	1	0	7	5	2	0	49
2	1	1	9	5	2	1	70
2	2	0	9	5	2	2	94
2	3	0	12	5	3	0	79
				5	3	1	110
3	0	0	8	5	3	2	140
3	0	1	11				
3	1	0	11	5	3	3	180
3	1	1	14	5	4	0	130
3	2	0	14	5	4	1	170
3	2	1	17	5	4	2	220
				5	4	3	280
4	0	0	13	5	4	4	350
4	0	1	17				
4	1	0	17	5	5	0	240
4	1	1	21	5	5	1	350
4	1	2	26	5	5	2	540
				5	5	3	920
				5	5	4	1600
				5	5	5	≥2400

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

14.4.16.5.3.1 Membrane Filter Procedure

The procedure for the membrane filter method is described below:

1. Sample filtration
   A. Select a filter, and aseptically separate it from the sterile package.
   B. Place the filter on the support plate with the grid side up.
   C. Place the funnel assembly on the support; secure as needed (see Figure 14.17).
   D. Pour 100 mL of sample or serial dilution onto the filter. Apply vacuum.

   Note: The sample size or necessary serial dilution should produce a growth of 20 to 60 fecal coliform colonies on at least 1 filter. The selected dilutions must also be capable of showing permit excursions.

   E. Allow all of the liquid to pass through the filter.
   F. Rinse the funnel and filter with three portions (20 to 30 mL) of sterile, buffered dilution water. (Allow each portion to pass through the filter before the next addition.)

   Note: Filtration units should be sterile at the start of each filtration series and should be sterilized

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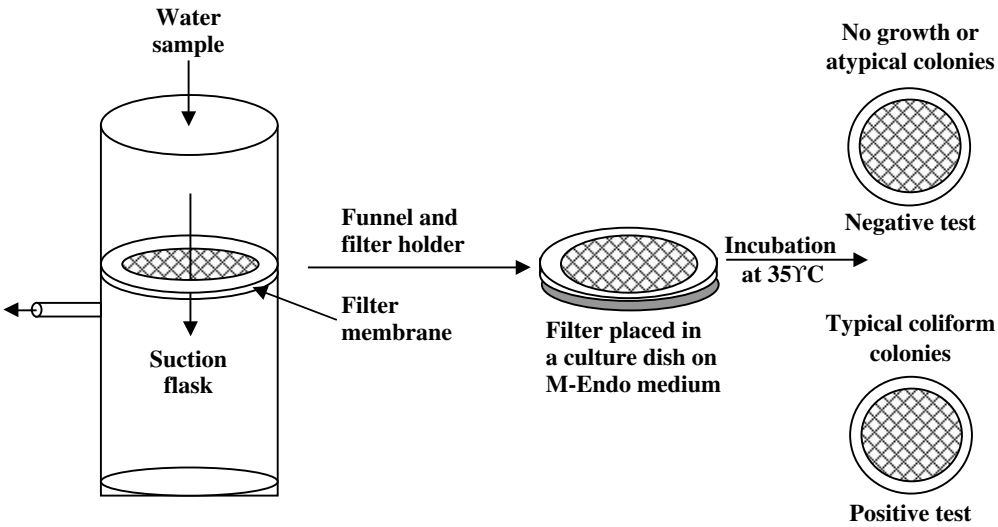

FIGURE 14.17 Diagram of membrane filter technique for coliform testing. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

again if the series is interrupted for 30 minutes or more. A rapid interim sterilization can be accomplished by 2 minutes exposure to ultraviolet (UV) light, flowing steam or boiling water.

2. Incubation
   A. Place absorbent pad into culture dish using sterile forceps.
   B. Add 1.8 to 2.0 mL M-FC media to the absorbent pad.
   C. Discard any media not absorbed by the pad.
   D. Filter sample through sterile filter.
   E. Remove filter from assembly. Place on absorbent pad (grid up).
   F. Cover culture dish.
   G. Seal culture dishes in a weighted plastic bag.
   H. Incubate filters in a water bath for 24 h at 44.5 ± 0.2°C.

14.4.16.5.3.2 Colony Counting

Upon completion of the incubation period, the surface of the filter will have growths of both fecal coliform and nonfecal coliform bacterial colonies. The fecal coliform will appear blue in color, while nonfecal coliform colonies will appear gray or cream colored.

When counting the colonies, the entire surface of the filter should be scanned using a 10× to 15× binocular, wide-field dissecting microscope.

The desired range of colonies, for the most valid fecal coliform determination is 20 to 60 colonies/filter. If multiple sample dilutions are used for the test, counts for each filter should be recorded on the laboratory data sheet:

1. Too many colonies — Filters that show a growth over the entire surface of the filter with no individually identifiable colonies should be recorded as confluent growth. Filters that show a very high number of colonies (greater than 200) should be recorded as too numerous to count (TNTC).
2. Not enough colonies — If no single filter meets the desired minimum colony count (20 colonies), the sum of the individual filter counts and the respective sample volumes can be used in the formula to calculate the colonies/100 mL.

Note: In each of these cases, adjustments in sample dilution volumes should be made to ensure future tests meet the criteria for obtaining a valid test result.

14.4.16.5.3.3 Calculation

The fecal coliform density can be calculated using the following formula:

$$\text{Colonies/100 mL} = \frac{\text{Colonies Counted}}{\text{Sample Volume (mL)}} \times 100 \text{ mL} \tag{14.13}$$

EXAMPLE 14.8

Problem:

Using the data shown below, calculate the colonies per 100 mL for the influent and effluent samples noted.

Sample Location	Influent Sample Dilutions			Effluent Sample Dilutions		
Sample (mL)	1.0	0.1	0.01	10	1.0	0.1
Colonies counted	97	48	16	10	5	3

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Solution:

Step 1: Influent sample

Select the influent sample filter that has a colony count in the desired range (20 to 60). Because one filter meets this criterion, the remaining influent filters that did not meet the criterion are discarded:

$$\text{Colonies/100 mL} = \frac{48 \text{ colonies}}{0.1 \text{ mL}} \times 100 \text{ mL}$$

$$= 48{,}000 \text{ colonies/100 mL}$$

Step 2: Effluent sample

Because none of the filters for the effluent sample meets the minimum test requirement, the colonies/100 mL must be determined by totaling the colonies on each filter and the sample volumes used for each filter.

$$\text{Total colonies} = 10 + 5 + 3 = 18 \text{ colonies}$$

$$\text{Total sample} = 10.0 \text{ mL} + 1.0 \text{ mL} + 0.1 \text{ mL} = 11.1 \text{ mL}$$

$$\text{Colonies/100 mL} = \frac{18 \text{ colonies}}{11.1 \text{ mL}} \times 100 \text{ mL}$$

$$= 162 \text{ colonies/100 mL}$$

Note: The EPA criterion for fecal coliform bacteria in bathing waters is a logarithmic mean of 200/100 mL, based on the minimum of 5 samples taken over a 30-d period, with not more than 10% of the total samples exceeding 400/100 mL. Because shellfish may be eaten without being cooked, the strictest coliform criterion applies to shellfish cultivation and harvesting. EPA criterion states that the mean fecal coliform concentration should not exceed 14/100 mL, with not more than 10% of the samples exceeding 43/100 mL.

14.4.16.5.3.4 Interferences

Large amounts of turbidity, algae, or suspended solids may interfere with this technique, blocking the filtration of the sample through the membrane filter. Dilution of these samples to prevent this problem may make the test inappropriate for samples with low fecal coliform densities. This is because the sample volumes after dilution may be too small to give representative results. The presence of large amounts of noncoliform group bacteria in the samples may also prohibit the use of this method.

Note: Many NPDES discharge permits require fecal coliform testing. Results for fecal coliform testing must be reported as a geometric mean (average) of all the test results obtained during a reporting period. A geometric mean, unlike an arithmetic mean or average, dampens the effect of very high or low values that otherwise might cause a non-representative result.

14.4.17 Apparent Color Testing/Analysis

As mentioned, color in water often originates from organic sources: decomposition of leaves and other forest debris such as bark, pine needles, etc. Tannins and lignins, organic compounds, dissolve in water. Some organics bond to iron to produce soluble color compounds. Biodegrading algae from recent bloom may cause significant color. Though less likely a source of color in water, possible inorganic sources of color are salts of iron, copper, and potassium permanganate added in excess at the treatment plant.

Note: Noticeable color is an objectionable characteristic that makes the water psychologically unacceptable to the consumer.

Recall that true color is dissolved. It is measured colorimetrically and compared against an EPA color standard.

Apparent color may be caused by suspended material (turbidity) in the water. It is important to point out that even though it may also be objectionable in the water supply, it is not meant to be measured in the color analysis or test. Probably the most common cause of apparent color is particulate oxidized iron.

Over the years, several attempts to standardize the method of describing the apparent color of water using comparisons to color standards have been made. *Standard Methods* recognizes the Visual Comparison Method as a reliable method of analyzing water from the distribution system.

One of the visual comparison methods is the Forel-Ule color scale, consisting of a dozen shades ranging from deep blue to khaki green, typical of offshore and coastal bay waters. By using established color standards, people in different areas can compare test results.

Another visual comparison method is the Borger color system, which provides an inexpensive, portable color reference for shades typically found in natural waters. It can also be used for its original purpose — describing the colors of insects and larvae found in streams of lakes. This System also allows the recording of the color of algae and bacteria on streambeds.

Note: Do not leave color standard charts and comparators in direct sunlight.

Measured levels of color in water can serve as indicators for a number of conditions. For example, transparent water with a low accumulation of dissolved minerals and particulate matter usually appears blue, indicating low productivity. A yellow to brown color normally indicates that the water contains dissolved organic materials, humic substances from soil, peat, or decaying plant material. Deeper yellow to reddish colors indicates some algae and

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dinoflagellates. A variety of yellows, reds, browns, and grays are indicative of soil runoff.

Note: Color of itself has no health significance in drinking waters. A secondary MCL is set at 15 color units, and it is recommended that community supplies provide water that has less color.

To ensure reliable and accurate descriptions of apparent color, use a system of color comparisons that is reproducible and comparable to the systems used by other groups.

In treating for color in water, alum and ferric coagulation is often effective. It removes apparent color and often much of the true color. Oxidation of color causing compounds to a noncolored version is sometimes effective. Activated carbon treatment may adsorb some of the organics causing color. For apparent color problems, filtration is usually effective in trapping the colored particles.

14.4.18 Odor Analysis of Water

Odor is expected in wastewater. Any water containing waste, especially human waste, has a detectable (expected) odor associated with it. Odor in a raw water source (for potable water) is caused by a number of constituents. For example, chemicals that may come from municipal and industrial waste discharges, or natural sources such as decomposing vegetable matter or microbial activity may cause odor problems. Odor affects the acceptability of drinking water, the aesthetics of recreation water, and the taste of aquatic foodstuffs.

The human nose can accurately detect a wide variety of smells, which is the best odor-detection and testing device presently available. To measure odor, collect a sample in a large-mouthed jar. After waving off the air above the water sample with you hand, smell the sample. Use the list of odors provided in Table 14.11 — a system of qualitative description that helps monitors describe and record detected odors to describe the smells. Record all observations. (see *Standard Methods*).

In treating for odor in water, removal depends upon the source of the odor. Some organic substances that cause odor can be removed with powdered activated carbon. If the odor is of gaseous origin, scrubbing (aeration) may remove it. Some odor-causing chemicals can be oxidized to odorless chemicals with chlorine, potassium permanganate, or other oxidizers. Settling may remove some material that when later dissolved in the water may have potential odor-causing capacity.

Unfortunately, the test for odor in water is subjective. There is no scientific means of measurement and other methods are not very accurate.

In testing odor in water intended for potable water use, a sample is generally heated to 60°C. Odor is observed and recorded. A threshold odor number (TON) is assigned. TON is found by using the following equation:

TABLE 14.11
Descriptions of Odors

Nature of Odor	Description	Examples
Aromatic	Spicy	Camphor; cloves; lavender
Balsamic	Flowery	Geranium; violet; vanilla
	Industrial wastes or treatments chlorinous	Chlorine
	Hydrocarbon	Oil refinery wastes
	Medicinal	Phenol and iodine
	Sulfur	Hydrogen sulfide
Disagreeable	Fishy	Dead algae
	Pigpen	Algae
	Septic	Stale sewage
Earthy	Damp earth	
	Peaty	Peat
Grassy	Crushed grass	
Musty	Decomposing straw	
	Moldy	Damp cellar
Vegetable	Root vegetables	

Source: From American Public Health Association, *Standard Methods for the Examination of Water and Wastewater*, 20th ed., Washington, D.C., 1998.

$$\text{TON} = \frac{\text{Total Volume of Water Sample}}{\text{Lowest Sample Volume with Odor}} \quad (14.14)$$

14.4.19 Chlorine Residual Testing/Analysis

Chlorination is the most widely used means of disinfecting water in the U.S. When chlorine gas is dissolved into (pure) water, if forms hypochlorous acid, hypochlorite ion, and hydrogen chloride (hydrochloric acid).

The total concentration of HOCl and OCl ion is known as free chlorine residual.

Currently, CFR cites seven approved methods for determination of TRC:

1. N,N diethyl-p-phenylenediamine- (DPD) spectrophotometric
2. Titrimetric — amperometric direct
3. Titrimetric — iodometric direct
4. Titrimetric — iodometric back
   A. Starch iodine end point — iodine titrant
   B. Starch iodine end point — iodate titrant
5. Amperometric end point
6. DPD-ferrous ammonium sulfate (FAS) titration
7. Chlorine electrode

All of these test procedures are approved methods and, unless prohibited by the plant's NPDES discharge permit, can be used for effluent testing. Based on current most popular method usage in the U.S., discussion is limited to the following:

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1. DPD-spectrophotometric
2. DPD-FAS titration
3. Titrimetric — amperometric direct

Note: Treatment facilities required to meet nondetectable TRC limitations must use one of the test methods specified in the plant's NPDES discharge permit.

For information on any of the other approved methods, refer to the appropriate reference cited in the CFR.

14.4.19.1 DPD-Spectrophotometric

DPD reacts with chlorine to form a red color. The intensity of the color is directly proportional to the amount of chlorine present. This color intensity is measured using a colorimeter or spectrophotometer. This meter reading can be converted to a chlorine concentration using a graph developed by measuring the color intensity produced by solutions with precisely known concentrations of chlorine. In some cases, spectrophotometer or colorimeters are equipped with scales that display chlorine concentration directly. In these cases, there is no requirement to prepare a standard reference curve.

If the direct reading colorimeter is not used, chemicals that are required to be used include:

1. Potassium dichromate solution 0.100N
2. Potassium iodine crystals
3. Standard FAS solution 0.00282 N
4. Concentrated phosphoric acid
5. Sulfuric acid solution (1 + 5)
6. Barium diphenylamine sulfonate 0.1%

If an indicator is not used, DPD indicator and phosphate buffer (DPD prepared indicator — buffer + indicator together) are required.

In conducting the test, one of the following is required:

1. Direct readout colorimeter designed to meet the test specifications
2. Spectrophotometer (wavelength of 515 nm and light path of at least 1 cm)
3. Filter photometer with a filter having maximum transmission in the wavelength range of 490 to 520 nm and a light path of at least 1 cm

In addition, for direct readout colorimeter procedures, a sample test vial is required. When the direct readout colorimeter procedure is not used, the equipment required includes:

1. 250 mL Erlenmeyer flask
2. 10 mL measuring pipettes
3. 15 mL test tubes
4. 1 mL pipettes (graduated to 0.1 mL)
5. Sample cuvettes with 1 cm light path

Note: A cuvette is a small, often tubular laboratory vessel that is usually made of glass.

14.4.19.1.1 Procedure

Note: For direct readout colorimeters, follow the procedure supplied by the manufacturer.

The standard procedure for using spectrophotometer or colorimeter is listed below:

1. Prepare a standard curve for TRC concentrations from 0.05 to 4.0 mg/L — chlorine versus percent transmittance.

Note: Instructions on how to prepare the TRC concentration curve or a standard curve is normally included in the spectrophotometer manufacturer's operating instructions.

2. Calibrate the colorimeter in accordance with the manufacturer's instructions using a laboratory-grade water blank.
3. Add one prepared indicator packet (or tablet) of the appropriate size to match sample volume to a clean test tube or cuvette or one of the following:
   A. Pipette 0.5 mL phosphate buffer solution.
   B. Pipette 0.5 mL DPD indicator solution.
   C. 0.1-g potassium iodide crystals to a clean tube or cuvette.
4. Add 10 mL of sample to the cuvette.
5. Stopper the cuvette. Swirl to mix the contents well.
6. Let stand for 2 min.
7. Verify the wavelength of the spectrophotometer or colorimeter. Check and set the 0% *T* using the laboratory-grade water blank.
8. Place the cuvette in instrument, read %*T*, and record reading.
9. Determine the milligrams per liter of TRC from standard curve.

Note: Calculations are not required in this test because the milligrams per liter of TRC is read directly from the meter or from the graph.

14.4.19.2 DPD-FAS Titration

The amount of FAS solution required to just remove the red color from a TRC sample that has been treated with DPD indicator can be used to determine the concentration of chlorine in the sample. This is known as a titrimetric test procedure.

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The chemicals used in the test procedure include the following:

1. DPD prepared indicator (buffer and indicator together)
2. Potassium dichromate solution 0.100N
3. Potassium iodide crystals
4. Standard FAS solution 0.00282 N
5. Concentrated phosphoric acid
6. Sulfuric acid solution (1 + 5)
7. Barium diphenylamine sulfonate 0.1%

Note: A DPD indicator or phosphate buffer is not required if a prepared indicator is used.

The equipment required for this text procedure includes the following:

1. 250 mL graduated cylinder
2. 5 mL measuring pipettes
3. 500 mL Erlenmeyer flask
4. 50 mL buret (graduate to 0.1 mL)
5. Magnetic stirrer and stir bars

14.4.19.2.1 Procedure

The standard procedure for DPD-FAS titration is listed below:

1. Add the contents of a prepared indicator packet (or tablet) to the Erlenmeyer flask or one of the following:
   A. Pipette 5 mL phosphate buffer solution into an Erlenmeyer flask.
   B. Pipette 5 mL DPD indicator solution into the flask.
   C. 1-g potassium iodide crystals to the flask.
2. Add 100 mL of sample to the flask.
3. Swirl the flask to mix contents.
4. Let the flask stand for 2 minutes.
5. Titrate with FAS until the red color first disappears.
6. Record the amount of titrant.

The calculation required in this procedure is:

$$\text{TRC}\left(\text{mg/L}\right) = \text{mL of FAS used} \qquad (14.15)$$

14.4.19.3 Titrimetric–Amperometric Direct Titration

In this test procedure, phenylarsine oxide is added to a treated sample to determine when the test reaction has been completed. The volume of phenylarsine oxide (PAO) used can then be used to calculate the TRC.

The chemicals used for this procedure include:

1. PAO solution 0.00564 N
2. Potassium dichromate solution 0.00564 N
3. Potassium iodide solution 5%
4. Acetate buffer solution (pH 4.0)
5. Standard arsenite solution 0.1 N

The equipment used for this procedure includes:

1. 250 mL graduated cylinder
2. 5 mL measuring pipettes
3. Amperometric titrator

14.4.19.3.1 Procedure

The standard procedure for titrimetric–amperometric direct titration is listed below:

1. Prepare amperometric titrator according to manufacturer.
2. Add 200-mL sample.
3. Place container on titrator stand and turn on mixer.
4. Add 1-g potassium iodide crystals or 1 mL potassium iodide solution.
5. Pipette 1 mL of acetate buffer into the container.
6. Titrate with 0.0056 N PAO.

When conducting the test procedure, as the downscale end point is neared, slow the titrant addition to 0.1-mL increments, and note the titrant volume used after increment. When no needle movement is noted, the end point has been reached. Subtract the final increment from the buret reading to determine the final titrant volume.

For this procedure, the only calculation normally required is:

$$\text{TRC}\left(\text{mg/L}\right) = \text{mL PAO used} \qquad (14.16)$$

14.4.20 Fluorides

It has long been accepted that a moderate amount of fluoride ions (F^-) in drinking water contributes to good dental health; it has been added to many community water supplies throughout the U.S. to prevent dental caries in children's teeth. Fluoride is seldom found in appreciable quantities of surface waters and appears in groundwater in only a few geographical regions. Fluorides are used to make ceramics and glass. Fluoride is toxic to humans in large quantities, and to some animals.

The chemicals added to potable water in treatment plants are:

NaF	Sodium fluoride (solid)
Na_2SiF_6	Sodium silicofluoride (solid)
H_2SiF_6	Hyrofluosilicic acid (most widely used)

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Analysis of the fluoride content of water can be performed using the colorimetric method. In this test, fluoride ion reacts with zirconium ion and produces zirconium fluoride, which bleaches an organic red dye in direct proportion to its concentration. This can be compared to standards and read colorimetrically.

14.5 CHAPTER REVIEW QUESTIONS AND PROBLEMS

14.1. What equipment, apparatus, or instrumentation is required to perform the total solids test?
14.2. How soon after the sample is collected must the pH be tested?
14.3. What is a grab sample?
14.4. When is it necessary to use a grab sample?
14.5. What is a composite sample?
14.6. List three sample rules for sample collection.
14.7. What is the acceptable preservation method for suspended solids samples?
14.8 Most solids test methods are based upon changes in weight. What can cause changes in weight during the testing procedure?

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Part IV

Water and Water Treatment

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15 Potable Water Source

Because of huge volume and flow conditions, the quality of natural water cannot be modified significantly within the body of water. Accordingly, humans must augment nature's natural processes with physical, chemical, and biological treatment procedures. Essentially, this quality control approach is directed to the water withdrawn, which is treated, from a source for a specific use.

15.1 INTRODUCTION

Before presenting a discussion of potential potable water supplies available to us at the current time, it is important that we define potable water:

> Potable water is water fit for human consumption and domestic use, which is sanitary and normally free of minerals, organic substances, and toxic agents in excess of reasonable amounts for domestic usage in the area served, and normally adequate in quantity for the minimum health requirements of the persons served.

In regards to a potential potable water supply, the key words are quality and quantity. If we have a water supply that is unfit for human consumption, we have a quality problem. If we do not have an adequate supply of quality water, we have a quantity problem.

In this chapter we discuss the surface water and groundwater hydrology and the mechanical components associated with collection and conveyance of water from its source to the public water supply system for treatment. We also discuss development of well supplies.

To better comprehend the material presented in this chapter, we have provided the following list of key terms and their definitions.

15.1.1 Key Terms and Definitions

Surface water the water on the earth's surface as distinguished from water underground (groundwater).

Groundwater subsurface water occupying a saturated geological formation from which wells and springs are fed.

Hydrology the applied science pertaining to properties, distribution, and behavior of water.

Permeable a material or substance that water can pass through.

Overland flow the movement of water on and just under the earth's surface.

Surface runoff the amount of rainfall that passes over the surface of the earth.

Spring a surface feature where without the help of man, water issues from rock or soil onto the land or into a body of water, the place of issuance being relatively restricted in size.

Precipitation the process by which atmospheric moisture is discharged onto the earth's crust. Precipitation takes the form of rain, snow, hail, and sleet.

Water rights the rights, acquired under the law, to use the water accruing in surface or groundwater for a specified purpose in a given manner and usually within the limits of a given time period.

Drainage basin an area from which surface runoff or groundwater recharge is carried into a single drainage system. It is also called catchment area, watershed, and drainage area.

Watershed a drainage basin from which surface water is obtained.

Recharge area an area from which precipitation flows into underground water sources.

Raw water the untreated water to be used after treatment for drinking water.

Caisson large pipe placed in a vertical position.

Impermeable a material or substance water will not pass through.

Contamination the introduction into water of toxic materials, bacteria, or other deleterious agents that make the water unfit for its intended use.

Aquifer a porous, water-bearing geologic formation.

Water table the average depth or elevation of the groundwater over a selected area. The upper surface of the zone of saturation, except where that surface is formed by an impermeable body.

Unconfined aquifer an aquifer that sits on an impervious layer, but is open on the top to local infiltration. The recharge for an unconfined aquifer is local. It is also called a water table aquifer.

Confined aquifer an aquifer that is surrounded by formations of less permeable or impermeable material.

Porosity the ratio of pore space to total volume. That portion of a cubic foot of soil that is air space and could therefore contain moisture.

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Static level the height to which the water will rise in the well when the pump is not operating.

Pumping level the level at which the water stands when the pump is operating.

Drawdown the distance or difference between the static level and the pumping level. When the drawdown for any particular capacity well and rate pump bowls is determined, the pumping level is known for that capacity. The pump bowls are located below the pumping level so that they will always be underwater. When the drawdown is fixed or remains steady, the well is then furnishing the same amount of water as is being pumped.

Cone of depression as the water in a well is drawn down, the water near the well drains or flows into it. The water will drain further back from the top of the water table into the well as drawdown increases.

Radius of influence the distance from the well to the edge of the cone of depression; the radius of a circle around the well from which water flows into the well.

Annular space the space between the casing and the wall of the hole.

Specific yield the geologist's method for determining the capacity of a given well and the production of a given water-bearing formation, it is expressed as gallons per minute per foot of drawdown.

15.1.2 Hydrologic Cycle

To attain a better understanding how water is made available, an understanding of the hydrologic cycle (water cycle) is necessary (see Figure 15.1). The hydrologic cycle is a cycle without a beginning or an end. It transports the earth's water from one location to another. As shown in Figure 15.1, it consists of precipitation, surface runoff, infiltration, percolation, and evapotranspiration.

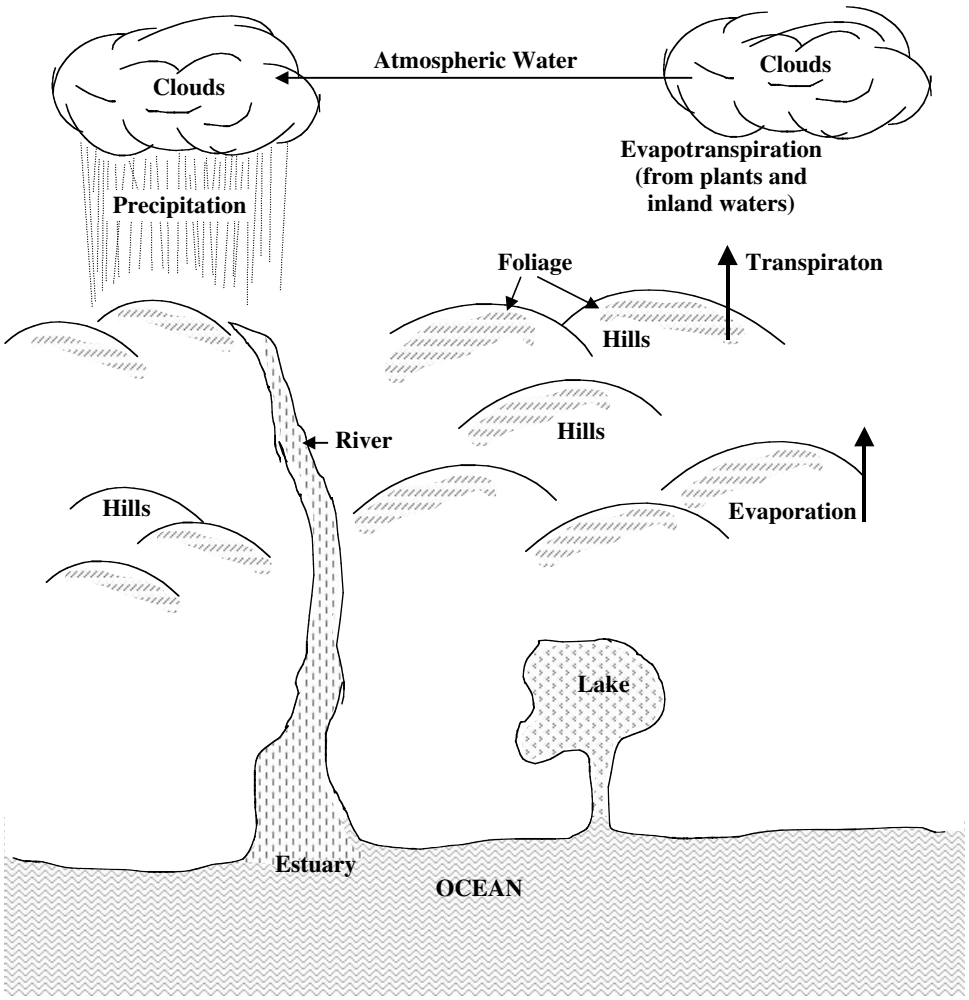

FIGURE 15.1 Natural water cycle. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

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In the hydrologic cycle, water from streams, lakes, and oceans evaporated by the sun, together with evaporation from the earth and transpiration from plants, furnishes the atmosphere with moisture. Masses of warm air laden with moisture are either forced to cooler upper regions or encounter cool air masses, where the masses condense and form clouds. This condensed moisture falls to earth in the form of rain, snow, and sleet. Another part of the precipitation runs off to streams and lakes, while a third part enters the earth to supply vegetation and rises through the plants to transpire from the leaves, and part seeps or percolates deeply into the ground to supply wells, springs, and the baseflow (dry weather flow) of streams.

The cycle constantly repeats itself — a cycle without end.

Note: How long water that falls from the clouds takes to return to the atmosphere varies tremendously. After a short summer shower, most of the rainfall on land can evaporate into the atmosphere in only a matter of minutes. A drop of rain falling on the ocean may take as long as 37,000 years before it returns to atmosphere, and some water has been in the ground or caught in glaciers for millions of years.

15.2 SOURCES OF WATER

Approximately 40 million mi^3 of water cover or reside within the earth. The oceans contain about 97% of all water on earth. The other 3% is freshwater: (1) snow and ice on the surface of earth contain about 2.25% of the water, (2) usable groundwater is approximately 0.3%, and (3) surface freshwater is less than 0.5%.

In the U.S., for example, average rainfall is approximately 2.6 ft (a volume of 5900 km^3). Of this amount, approximately 71% evaporates (about 4200 cm^3), and 29% goes to stream flow (about 1700 km^3).

Beneficial freshwater uses include manufacturing, food production, domestic and public needs, recreation, hydroelectric power production, and flood control. Stream flow withdrawn annually is about 7.5% (440 km^3). Irrigation and industry use almost half of this amount (3.4% or 200 km^3/year). Municipalities use only about 0.6% (35 km^3/year) of this amount.

Historically, in the U.S., water usage is increasing (as might be expected). For example, in 1990, 40 billion gal of freshwater were used. In 1975, the total increased to 455 billion gal. Projected use in 2002 was about 725 billion gal.

The primary sources of freshwater include the following:

1. Captured and stored rainfall in cisterns and water jars
2. Groundwater from springs, artesian wells, and drilled or dug wells
3. Surface water from lakes, rivers, and streams
4. Desalinized seawater or brackish groundwater
5. Reclaimed wastewater

Current federal drinking water regulations actually define three distinct and separate sources of freshwater. They are surface water, groundwater, and groundwater under the direct influence of surface water (GUDISW). This last classification is the result of the Surface Water Treatment Rule (SWTR). While the definition of what conditions constitute GUDISW is specific, it is not obvious. This classification is discussed in detail later.

15.3 SURFACE WATER

Surface waters are not uniformly distributed over the Earth's surface. In the U.S., for example, only about 4% of the landmass is covered by rivers, lakes, and streams. The volumes of these freshwater sources depend on geographic, landscape, and temporal variations, and on the impact of human activities.

Surface water is that water that is open to the atmosphere and results from overland flow (i.e., runoff that has not yet reached a definite stream channel). In other words, surface water is the result of surface runoff.

For the most part, surface (as used in the context of this text) refers to water flowing in streams and rivers. It also refers to the following:

1. Water stored in natural or artificial lakes,
2. Man-made impoundments, such as lakes, made by damming a stream or river
3. Springs that are affected by a change in level or quantity
4. Shallow wells that are affected by precipitation
5. Wells drilled next to or in a stream or river
6. Rain catchments
7. Muskeg and tundra ponds

15.3.1 Advantages and Disadvantages of Surface Water

The biggest advantage of using a surface water supply as a water source is that these sources are readily located; finding surface water sources does not demand sophisticated training or equipment. Many surface water sources have been used for decades and even centuries (e.g., in the U.S.), and considerable data are available on the quantity and quality of the existing water supply. Surface water is also generally softer (not mineral-laden), which makes its treatment much simpler.

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The most significant disadvantage of using surface water as a water source is pollution. Surface waters are easily contaminated (polluted) with microorganisms that cause waterborne diseases and chemicals that enter the river or stream from surface runoff and upstream discharges.

Another problem with many surface water sources is turbidity, which fluctuates with the amount of precipitation. Increases in turbidity increase treatment cost and operator time.

Surface water temperatures can be a problem because they fluctuate with ambient temperature, making consistent water quality production at a waterworks plant difficult.

Drawing water from a surface water supply might also present problems; intake structures may clog or become damaged from winter ice, or the source may be so shallow that it completely freezes in the winter.

Water rights cause problems as well; removing surface water from a stream, lake, or spring requires a legal right. The lingering, seemingly unanswerable question is who owns the water?

Using surface water as a source means that the purveyor is obligated to meet the requirements of the SWTR and Interim Enhanced Surface Water Treatment Rule (IESWTR). (Note: This rule only applies to large public water systems [PWSs] that serve more than 10,000 people. It tightened controls on disinfection by-products (DBPs) and turbidity and regulates *Cryptosporidium*.)

15.3.2 Surface Water Hydrology

To properly manage and operate water systems, a basic understanding of the movement of water and the things that affect water quality and quantity are important. In other words, a basic understanding of hydrology is essential. A discipline of applied science, hydrology includes several components, including the physical configuration of the watershed, the geology, soils, vegetation, nutrients, energy, wildlife, and the water.

The area from which surface water flows is called a drainage basin or catchment area. With a surface water source, this drainage basin is most often called in nontechnical terms a watershed. (When dealing with groundwater, we call this area a recharge area.)

Key Point: The area that directly influences the quantity and quality of surface water is called the drainage basin or watershed.

When you trace on a map the course of a major river from its meager beginnings on its seaward path, the fact that its flow becomes larger and larger is apparent. While every tributary brings a sudden increase, between tributaries, the river grows gradually from overland flow entering it directly (see Figure 15.2).

Not only does the river grow its whole watershed or drainage basin, but basically the land it drains into grows as well, in the sense that it embraces an ever-larger area.

The area of the watershed is commonly measured in square miles, sections, or acres. When taking water from a surface water source, knowing the size of the watershed is desirable.

15.3.3 Raw Water Storage

Raw water (i.e., water that has not been treated) is stored for single or multiple uses, such as navigation, flood control, hydroelectric power, agriculture, water supply, pollution abatement, recreation, and flow augmentation. The primary reason for storing water is to meet peak demands and to store water to meet demands when the flow of the source is below the demand. Raw water is stored in natural storage sites (such as lakes, muskeg, and tundra ponds) or in man-made storage areas such as dams.

The photos depicted in Figure 15.3A through Figure 15.3D show one man-made raw water source control method for agricultural and other uses that is currently being used. Figure 15.3A, shows Middle Two Medicine Lake that is snow and ice fed and connected by river to the Smaller Two Medicine Lake (not shown). Between the two lakes are many breathtaking waterfalls. Figure 15.3B shows Running Eagle Falls that plunges into the 157-mi Two Medicine River shown in Figure 15.3C. Figure 15.3D shows the man-made spillway downriver from Running Eagle Falls. The spillway controls flow at a set level for recreational, agricultural, grazing, and other uses.

Figure 15.4A through Figure 15.4D show another example of how raw water supplies are stored. Figure 15.4A and Figure 15.4B show views of Lake Whitehurst, Norfolk, VA. Lake Whitehurst is the primary potable water raw water supply reservoir for Norfolk and other local customers. Figure 15.4C and Figure 15.4D show the man-made spillway that controls the volume and level of water contained in the lake. The spillway is important to the homeowners bordering the lake, because it acts as a flood control mechanism, protecting properties from high water level damage. Lake Whitehurst not only provides a potable water source for Norfolk customers, but it also provides a pristine recreation area within the city limits.

As mentioned and shown in Figure 15.4C and Figure 15.4D, the spillway is man-made. Man-made spillways and dams are either masonry or embankment dams. If embankment dams are used, they are typically constructed of local materials with an impermeable clay core.

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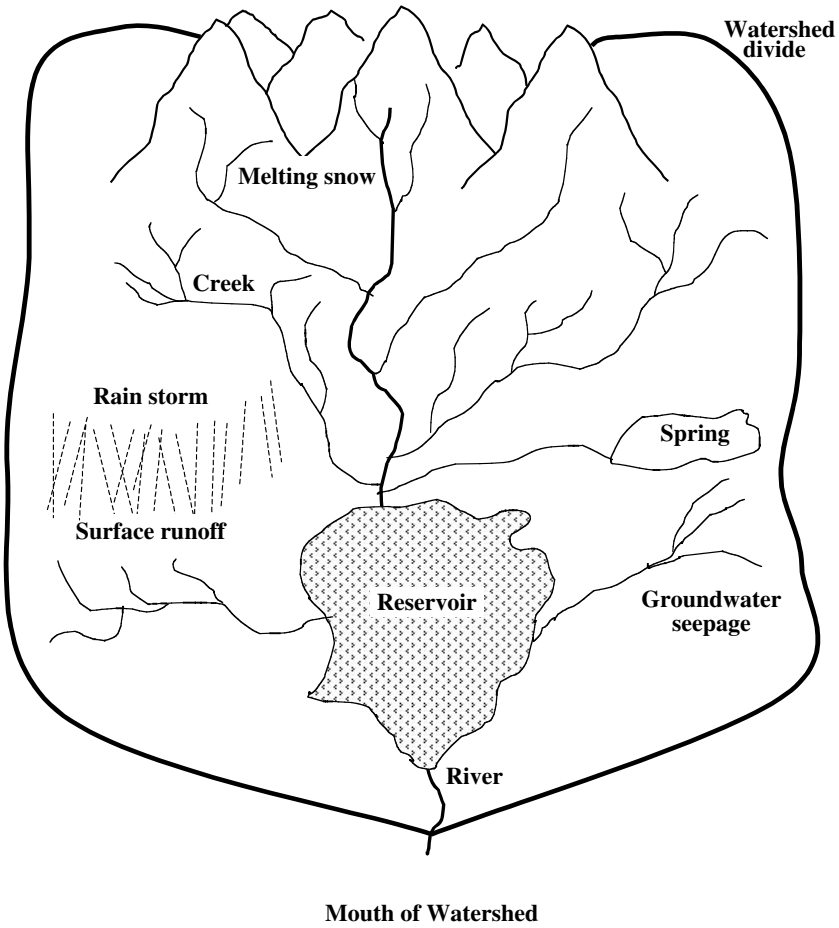

FIGURE 15.2 Watershed. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

FIGURE 15.3A Middle Two Medicine Lake, East Glacier National Park, Montana. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

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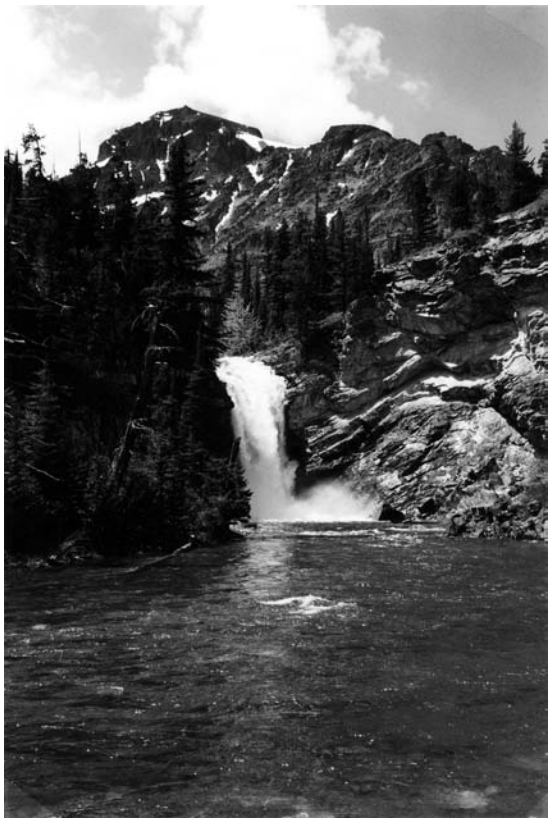

FIGURE 15.3B Running Eagle Falls, East Glacier National Park, Montana. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

15.3.4 Surface Water Intakes

Withdrawing water from a river, lake, or reservoir so that it may be conveyed to the first unit process of the treatment process requires an intake structure. Intakes have no standard design and range from a simple-pump suction pipe sticking out into the lake or stream to expensive structures costing several thousands of dollars. Typical intakes include submerged intakes, floating intakes, infiltration galleries, spring boxes, and roof catchments. Their primary functions are to supply the highest quality water from the source and to protect piping and pumps from, or clogging as a result of, wave action, ice formation, flooding, and submerged debris. A poorly conceived or constructed intake can cause many problems. Failure of the intake could result in water system failure.

On a small stream, the most common intake structures used are small gravity dams placed across the stream or a submerged intake. In the gravity dam type, a gravity line or pumps can remove water behind the dam. In the submerged intake type, water is collected in a diversion and carried away by gravity or pumped from a caisson.

Another common intake used on small and large streams is an end-suction centrifugal pump or submersible pump placed on a float. The float is secured to the bank, and the water is pumped to a storage area.

Often the intake structure placed in a stream is an infiltration gallery. The most common infiltration galleries are built by placing well screens or perforated pipe into the streambed. The pipe is covered with clean, graded gravel. When water passes through the gravel, coarse filtration removes a portion of the turbidity and organic material. The water collected by the perforated pipe then flows to a caisson placed next to the stream and is removed from the caisson by gravity or pumping.

Intakes used in springs are normally implanted into the water-bearing strata. They are then covered with clean, washed rock and sealed, usually with clay. The outlet is piped into a spring box.

In some locations, a primary source of water is rainwater. Rainwater is collected from the roof of buildings with a device called a roof catchment.

After determining that a water source provides a suitable quality and quantity of raw water, choosing an intake location includes determining the following:

1. Best quality water location
2. Dangerous currents
3. Sandbar formation
4. Wave action
5. Ice storm factors
6. Flood factors
7. Navigation channel avoidance
8. Intake accessibility
9. Power availability
10. Floating or moving object damage factors
11. Distance from pumping station
12. Upstream uses that may affect water quality

15.3.5 Surface Water Screens

Generally, screening devices are installed to protect intake pumps, valves, and piping. A coarse screen of vertical steel bars, with openings of 1 to 3 in. placed in a near-vertical position excludes large objects. It may be equipped with a trash truck rack rake to remove accumulated debris. A finer screen, one with 3/8-in. opening, removes leaves, twigs, small fish, and other material passing through the bar rack. Traveling screens consist of wire mesh trays that retain solids as the water passes through them. Drive chain and sprockets raise the trays into a head enclosure, where the debris is removed by water sprays. The screen travel pattern is intermittent and controlled by the amount of accumulated material.

Note: When considering what type of screen should be employed, the most important consideration is ensuring that they can be easily maintained.

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FIGURE 15.3C Two Medicine River, East Glacier Park, Montana. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

FIGURE 15.3D Human-made spillway, Two Medicine River, Glacier National Park, Montana. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

15.3.6 Surface Water Quality

Surface waters should be of adequate quality to support aquatic life and be aesthetically pleasing, and waters used as sources of supply should be treatable by conventional processes to provide potable supplies that can meet the drinking water standards. Many lakes, reservoirs, and rivers are maintained at a quality suitable for swimming, water skiing, boating, and drinking water.

Whether the surface water supply is taken from a river, stream, lake, spring, impoundment, reservoir, or dam, surface water quality varies widely, especially in rivers, streams, and small lakes. These water bodies are not only susceptible to waste discharge contamination, but also to flash contamination (can occur almost immediately and not necessarily over time). Lakes are subject to summer/winter stratification (turnover) and algal blooms. Pollution sources range from runoff (agricultural, residential, and urban) to spills, municipal and industrial wastewater discharges, recreational users, as well as from natural occurrences. Surface water supplies are difficult to protect from contamination and must always be treated.

15.4 GROUNDWATER

As mentioned, part of the precipitation that falls on land infiltrates the land surface, percolates downward through the soil under the force of gravity, and becomes groundwater. Groundwater, like surface water, is extremely important to the hydrologic cycle and to our water supplies.

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FIGURE 15.4A Lake Whitehurst, Norfolk, Virginia. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

FIGURE 15.4B Lake Whitehurst, Norfolk, Virginia. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

Almost half of the people in the U.S. drink public water from groundwater supplies. Overall, more water exists as groundwater than surface water in the U.S., including the water in the Great Lakes. Sometimes pumping it to the surface is not economical, and in recent years, pollution of groundwater supplies from improper disposal has become a significant problem.

We find groundwater in saturated layers called aquifers under the earth's surface. Three types of aquifers exist: unconfined, confined, and springs.

Aquifers are made up of a combination of solid material such as rock and gravel and open spaces called pores. Regardless of the type of aquifer, the groundwater in the aquifer is in a constant state of motion. This motion is caused by gravity or by pumping.

The actual amount of water in an aquifer depends upon the amount of space available between the various grains of material that make up the aquifer. The amount of space available is called porosity. The ease of movement through an aquifer is dependent upon how well the pores are connected. For example, clay can hold a lot of water and has high porosity, but the pores are not connected, so water moves through the clay with difficulty. The ability of an aquifer to allow water to infiltrate is called permeability.

The aquifer that lies just under the earth's surface is called the zone of saturation, an unconfined aquifer (see

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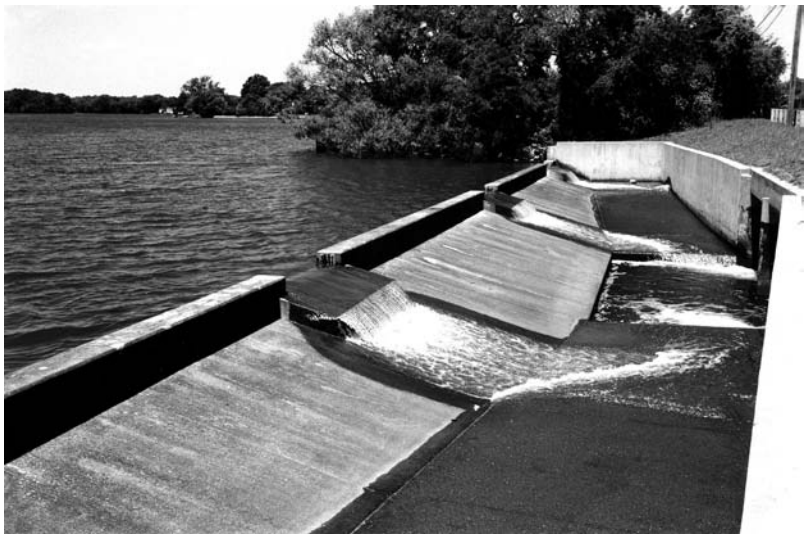

FIGURE 15.4C Lake Whitehurst Spillway, Norfolk, Virginia. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

FIGURE 15.4D Close-up view of Lake Whitehurst Spillway, Norfolk, Virginia. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

Figure 15.5). The top of the zone of saturation is the water table. An unconfined aquifer is only contained on the bottom and is dependent on local precipitation for recharge. This type of aquifer is often called a water table aquifer.

Unconfined aquifers are a primary source of shallow well water (see Figure 15.5). These wells are shallow (and not desirable as a public drinking water source). They are subject to local contamination from hazardous and toxic materials — fuel and oil and septic tanks and agricultural runoff providing increased levels of nitrates and microorganisms. These wells may be classified as groundwater under direct influence of surface water (GUDISW) and require treatment for control of microorganisms.

A confined aquifer is sandwiched between two impermeable layers that block the flow of water. The water in a confined aquifer is under hydrostatic pressure. It does not have a free water table (see Figure 15.6).

Confined aquifers are called artesian aquifers. Wells drilled into artesian aquifers are called artesian wells and commonly yield large quantities of high quality water. An artesian well is any well where the water in the well casing would rise above the saturated strata. Wells in confined aquifers are normally referred to as deep wells and are not generally affected by local hydrological events.

A confined aquifer is recharged by rain or snow in the mountains where the aquifer lies close to the surface of the earth. Because the recharge area is some distance from

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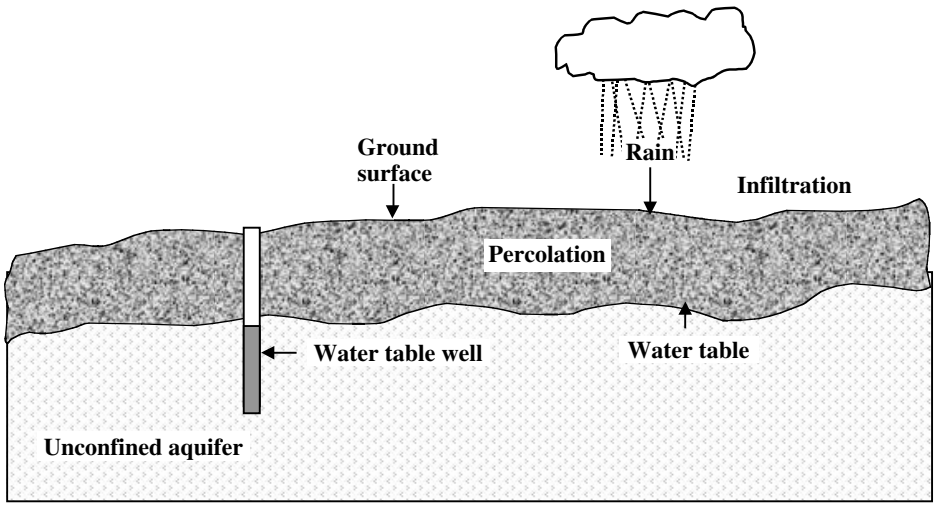

FIGURE 15.5 Unconfined aquifer. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

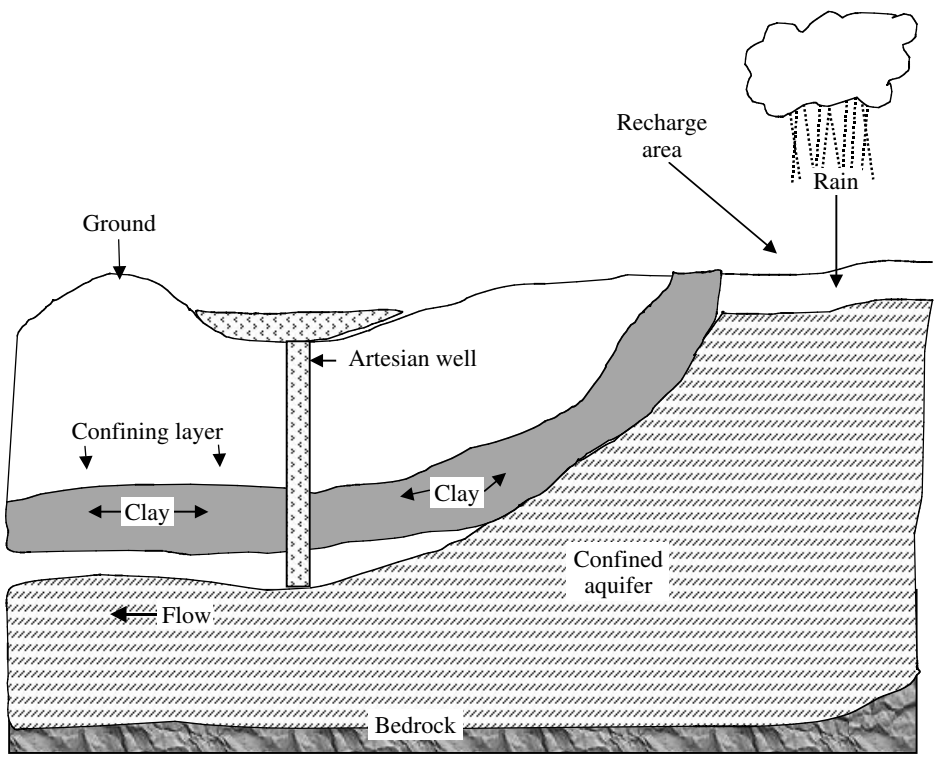

FIGURE 15.6 Confined aquifer. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

areas of possible contamination, the possibility of contamination is usually very low. However, once contaminated, confined aquifers may take centuries to recover.

Groundwater naturally exits the earth's crust in areas called springs. The water in a spring can originate from a water table aquifer or a confined aquifer. Only water from a confined spring is considered desirable for a public water system.

15.4.1 Groundwater Quality

Generally, groundwater possesses high chemical, bacteriological, and physical quality. When pumped from an aquifer composed of a mixture of sand and gravel, if not directly influenced by surface water, groundwater is often used without filtration. It can also be used without disinfection if it has a low coliform count. However, groundwater

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can become contaminated. When septic systems fail, saltwater intrudes, improper disposal of wastes occurs, improperly stockpiled chemicals leach, underground storage tanks leak, hazardous materials spill, fertilizers and pesticides are misplaced, and when mines are improperly abandoned, groundwater can become contaminated.

To understand how an underground aquifer becomes contaminated, you must understand what occurs when pumping is taking place within the well. When groundwater is removed from its underground source (i.e., from the water-bearing stratum) via a well, water flows toward the center of the well. In a water table aquifer, this movement causes the water table to sag toward the well. This sag is called the cone of depression. The shape and size of the cone depends on the relationship between the pumping rate and the rate at which water can move toward the well. If the rate is high, the cone is shallow, and its growth stabilizes. The area that is included in the cone of depression is called the cone of influence, and any contamination in this zone will be drawn into the well.

15.5 GUDISW

GUDISW is not classified as a groundwater supply. A supply designated as GUDISW must be treated under the state's surface water rules rather than the groundwater rules.

The SWTR of the Safe Drinking Water Act requires each site to determine which groundwater supplies are influenced by surface water (i.e., when surface water can infiltrate a groundwater supply and could contaminate it with *Giardia*, viruses, turbidity, and organic material from the surface water source). To determine whether a groundwater supply is under the direct influence of surface water, the U.S. Environmental Protection Agency (EPA) has developed procedures that focus on significant and relatively rapid shifts in water quality characteristics, including turbidity, temperature, and pH. When these shifts can be closely correlated with rainfall or other surface water conditions, or when certain indicator organisms associated with surface water are found, the source is said to be under the direct influence of surface water.

15.6 SURFACE WATER QUALITY AND TREATMENT REQUIREMENTS

PWSs must comply with applicable federal and state regulations and must provide quantity and quality water supplies including proper treatment (where and when required) and competent and qualified waterworks operators.

EPA's regulatory requirements insist that all public water systems using any surface water or GUDISW must disinfect and may be required by the state to filter, unless the water source meets certain requirements and site-specific conditions. Treatment technique requirements are established in lieu of maximum contaminant levels (MCLs) for *Giardia*, viruses, heterotrophic plate count bacteria, *Legionella,* and turbidity. Treatment must achieve at least 99.9% removal (3-log removal) and/or inactivation of *Giardia lamblia* cysts and 99.9% removal and/or inactivation of viruses.

Qualified operators (as determined by the state) must operate all systems. To avoid filtration, waterworks must satisfy the following criteria:

1. Fecal coliform concentration must not exceed 20/100 mL, or the total coliform concentration must not exceed 100/100 mL before disinfection in more than 10% of the measurements for the previous 6 months, calculated each month.
2. Turbidity levels must be measured every 4 h by grab samples or continuous monitoring. The turbidity level may not exceed 5 nephelometric turbidity units (NTUs). If the turbidity exceeds 5 NTUs, the water supply system must install filtration, unless the state determines that the event is unusual or unpredictable, and the event does not occur more than twice in any 1 year or 5 times in any consecutive 10 years.

When a choice of water sources exists for consideration, the source must present minimal risks of contamination from wastewaters and contain a minimum of impurities that may be hazardous to health. Acute (immediate) health effects such as those presented by exposure to *Giardia lamblia* and chronic (those that take longer to affect health) effects must be guarded against. MCLs must be monitored to ensure that the maximum permissible level of contaminant in water is not exceeded.

Note: Primary MCL is based on health considerations. Secondary MCL is based on aesthetic considerations (taste, odor, and appearance).

The PWS must also provide water free of pathogens (disease-causing microorganisms; e.g., bacteria, protozoa, spores, viruses, etc.). Chemical quality must also be monitored to ensure prevention of inorganic and organic contamination.

In addition to the requirements listed to this point, in 1996, EPA finalized the Stage 1 Disinfectants/Disinfection By-products (D/DBPs) and IESWTR rules and implemented them in 1998. These amendments tighten controls on DBPs and turbidity and regulate *Cryptosporidium.* Highlights of these changes include the following:

1. Stage 1 D/DBP Rule
   a. Tightens the total trihalomethane standard to 0.080 mg/L
   b. Sets new DBP standards for five haloacetic acids (0.060 mg/L), chlorite (1.0 mg/L), and bromate (0.010 mg/L)

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c. Establishes new standards for disinfectant residuals (4.0 mg/L for chlorine, 4.0 mg/L for chloramines, and 0.8 mg/L for chlorine dioxide)
d. Requires systems using surface water or GUDISW to implement enhanced coagulation or softening to remove DBP precursors unless systems meet alternative criteria
e. Applies to all community and nontransient-noncommunity systems that disinfect, including those serving fewer than 10,000 people
   i. MCLGs
      For maximum contaminant level goals (MCLGs), however, EPA opted to retain the chloroform MCLG at 0 instead of loosening it to 0.3 mg/L as set forth in the Spring 1998 Notice of Data Availability. The EPA also loosened the chlorite MCLG from 0.08 to 0.8 mg/L, loosened the maximum residual disinfectant level goal for chlorine dioxide from 0.3 to 0.8 mg/L, and set no MCLG for the DBP chloral hydrate (control of which will be covered by the other requirements).
   ii. Chloroform
      In dropping its plan to loosen the chloroform MCLG, EPA has backed away (for now) from its first attempt to set a level higher than zero MCLG for a carcinogenic contaminant, opting for more time to allow the issue to be discussed by stakeholders and the Science Advisory Board, which is slated to produce a chloroform report by November 1999. EPA outlined what it termed a compelling case for recognizing a safe (or threshold) exposure level for chloroform, one of the regulated trihalomethanes (THMs).

2. IESWT Rule
   This treatment optimization rule, which only applies to large (those serving more than 10,000 people) PWSs that use surface water or GUDISW, is the first to directly regulate *Cryptosporidium* (crypto). The rule:
   a. Sets a crypto MCLG of 0
   b. Requires systems that filter to remove 99% (2 log) of crypto oocysts
   c. Adds crypto control to watershed protection requirements for systems operating under filtration waivers
   d. Is particular to the genus *Cryptosporidium,* not to the *Cryptosporidium parvum* species
   i. Turbidity
      The rule requires continuous turbidity monitoring of individual filters. It also tightens allowable turbidity limits for combined filter effluent, cutting the maximum from 5 to 1 NTUs and the average monthly limit from 0.5 to 0.3 NTU.
   ii. Benchmarking
      Systems must determine within 15 months of promulgation whether they must establish a disinfection benchmark to ensure maintenance of microbial protection as systems comply with new DBP standards. Because the determination is based on whether the PWS exceeds annual average levels of THMs or haloacetic acids, systems that lack these data must begin collecting them within 3 months of promulgation to have 1 year's worth by the 15-month deadline.
      The rule also requires states to conduct periodic sanitary surveys of all surface water systems regardless of size, and covers all new treated-water reservoirs.
3. Regulatory Deadlines
   Large surface water systems (those serving over 10,000) must comply with the Stage 1 D/DBP and IESWT rules by December 2001. Smaller surface water systems and all groundwater systems must comply with the stage 1 D/DBP Rule by December 2003.

15.7 PUBLIC WATER SYSTEM USE REQUIREMENTS

Many factors affect the use of water, including climate, economic conditions, type of community (i.e., residential, commercial, industrial), integrity of the distribution system (waste pressure or leaks in the system), and water cost.

In the U.S., the typical per capita usage is approximately 150 gal/d per person. Each residential connection requires approximately 400 gal/d per connection. Keep in mind that fire-fighting requirements at a standard fire flow of 500 gal/min will use in 1 min what a family of five normally uses in 24 h.

Water pressure delivered to each service connection should (at a minimum) reach 20 psi under all flow conditions.

EPA provides the following facts and figures on public drinking water systems in the United States:[1]

> In the United States, there are approximately 170,000 public water systems. EPA classifies these water systems according to the number of people they serve, the source of their water and whether they serve the same customers

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year-round or on an occasional basis. The following statistics are based on information in the Safe Drinking Water Information System (SDWIS), for the year ended September 2000, as reported to EPA by the states.

Classifications

- Public water systems provide water for human consumption through pipes or other constructed conveyances to at least 15 service connections or serves an average of at least 25 people for at least 60 days a year. EPA has defined three types of public water systems:
- Community Water Systems (CWS): A public water system that supplies water to the same population year-round.
- Non-Transient Non-Community Water System (NTNCWS): A public water system that regularly supplies water to at least 25 of the same people at least 6 months per year, but not year-round. Some examples are schools, factories, office buildings, and hospitals, which have their own water systems.
- Transient Non-Community Water System (TNCWS): A public water system that provides water in a place such as a gas station or campground where people do not remain for long periods of time.

EPA also classifies water systems according to the number of people they serve:

- Very small water systems serve 25–500 people
- Small water systems serve 501–3,300 people
- Medium water systems serve 3,301–10,000 people
- Large water systems serve 10,001–100,000 people
- Very large water systems serve 100,001+ people

Number of Systems and Population Served for 2000

- 54,064 CWS served 263.9 million people
- 19,738 NTNCWS served 6.9 million people
- 93,210 TNCWS served 12.9 million people

1. Community Water System (CWS):

   Source of water:

   - 11,403 systems relied on surface water, serving 178.1 million people
   - 42,661 systems relied on groundwater, serving 85.9 million people

   System size:

   - 15% of CWS are very large, large, or medium, serving 90% of those who get their water from a CWS
   - 85% of CWS are small or very small; serving 10% of those who get their water from a CWS

2. Non-Transient Non-Community Water System (NTNCWS):

   Source of water:

   - 821 systems relied on surface water, serving 932,000 people
   - 19,738 systems relied on groundwater, serving 6.0 million people

   System size:

   - 99.4% of NTNCWS are small or very small, serving 76% of those served by NTNCWS
   - 0.6% of NTNCWS are medium, large, or very large, serving 24% of those served NTNCWS

3. Transient Non-Community Water Systems (TNCWS):

   Source of water:

   - 1,912 systems relied on surface water, serving 917,000 people
   - 91,298 systems relied on groundwater, serving 12.0 million people

   System size:

   - 99.8% TNCWS are small or very small, serving 78% of those served by TNCWS
   - 0.2% of TNCWS are medium, large, or very large, serving 22% of those served by TNCWS

15.8 WELL SYSTEMS

The most common method for withdrawing groundwater is to penetrate the aquifer with a vertical well, and then draw or pump the water up to the surface.

In the past (and even at present), when a person wanted a well, he simply dug (or hired someone to dig) and hoped (gambled) that he would find water in a quantity suitable for his needs. Today, in most locations in the U.S., for example, developing a well supply usually involves a more complicated step-by-step process.

Local, state, and federal requirements specify the actual requirements for development of a well supply in the U.S. The standard sequence for developing a well

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supply generally involves a seven-step process. This process includes:

Step 1: Application — Depending on location, filling out and submitting an application (to the applicable authorities) to develop a well supply is standard procedure.

Step 2: Well site approval — Once the application has been made, local authorities check various local geological and other records to ensure that the siting of the proposed well coincides with mandated guidelines for approval.

Step 3: Well drilling — The well is then drilled.

Step 4: Preliminary engineering report — After the well is drilled and the results documented, a preliminary engineering report is made on the suitability of the site to serve as a water source. This procedure involves performing a pump test to determine if the well can supply the required amount of water. The well is generally pumped for at least 6 h at a rate equal to or greater than the desired yield. A stabilized drawdown should be obtained at that rate and the original static level should be recovered within 24 h after pumping stops. During this test period, samples are taken and tested for bacteriological and chemical quality.

Step 5: Submission of documents for review and approval — The application and test results are submitted to an authorized reviewing authority that determines if the well site meets approval criteria.

Step 6: Construction permit — If the site is approved, a construction permit is issued.

Step 7: Operation permit — When the well is ready for use, an operation permit is issued.

15.8.1 Well Site Requirements

To protect the groundwater source and provide high-quality safe water, the waterworks industry has developed standards and specifications for wells. The following listing includes industry standards and practices, as well as those items included in example State Department of Environmental Compliance regulations.

Note: Check with your local regulatory authorities to determine well site requirements.

1. Minimum well lot requirements
   a. 50 ft from well to all property lines
   b. All-weather access road provided
   c. Lot graded to divert surface runoff
   d. Recorded well plat and dedication document
2. Minimum well location requirements
   a. At least 50-ft horizontal distance from any actual or potential sources of contamination involving sewage
   b. At least 50-ft horizontal distance from any petroleum or chemical storage tank or pipeline or similar source of contamination, except where plastic type well casing is used, the separation distance must be at least 100 ft
3. Vulnerability assessment
   a. Wellhead area = 1000 ft radius from the well
   b. What is the general land use of the area (residential, industrial, livestock, crops, undeveloped, other)?
   c. What are the geologic conditions (sinkholes, surface, subsurface)?

15.8.2 Types of Wells

Water supply wells may be characterized as shallow or deep. In addition, wells are classified as follows:

1. Class I — Cased and grouted to 100 ft
2. Class II A — Cased to a minimum of 100 ft and grouted to 20 ft
3. Class II B — Cased and grouted to 50 ft

Note: During the well development process, mud/silt forced into the aquifer during the drilling process is removed, allowing the well to produce the best-quality water at the highest rate from the aquifer.

15.8.2.1 Shallow Wells

Shallow wells are those that are less than 100 ft deep. Such wells are not particularly desirable for municipal supplies. This is because the aquifers they tap are likely to fluctuate considerably in depth, making the yield somewhat uncertain. Municipal wells in such aquifers cause a reduction in the water table (or phreatic surface) that affects nearby private wells, which are more likely to utilize shallow strata. Such interference with private wells may result in damage suits against the community. Shallow wells may be dug, bored, or driven.

15.8.2.1.1 Dug Wells

Dug wells are the oldest type of well and date back many centuries; they are dug by hand or by a variety of unspecialized equipment. They range in size from approximately 4 to 15 ft in diameter and are usually about 20 to 40 ft deep. Such wells are usually lined or cased with concrete or brick. Dug wells are prone to failure from drought or heavy pumpage. They are vulnerable to contamination and are not acceptable as a public water supply in many locations.

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15.8.2.1.2 Driven Wells

Driven wells consist of a pipe casing terminating in a point slightly greater in diameter than the casing. The pointed well screen and the lengths of pipe attached to it are pounded down or driven in the same manner as a pile, usually with a drop hammer, to the water-bearing strata. Driven wells are usually 2 to 3 in. in diameter and are used only in unconsolidated materials. This type of shallow well is not acceptable as a public water supply.

15.8.2.1.3 Bored Wells

Bored wells range from 1 to 36 in. in diameter and are constructed in unconsolidated materials. The boring is accomplished with augers (either hand or machine driven) that fill with soil and then are drawn to the surface to be emptied. The casing may be placed after the well is completed (in relatively cohesive materials), but must advance with the well in noncohesive strata. Bored wells are not acceptable as a public water supply.

15.8.2.2 Deep Wells

Deep wells are the usual source of groundwater for municipalities. Deep wells tap thick and extensive aquifers that are not subject to rapid fluctuations in water (piezometric surface — the height to which water will rise in a tube penetrating a confined aquifer) level and provide a large and uniform yield. Deep wells typically yield water of more constant quality than shallow wells, although the quality is not necessarily better. Deep wells are constructed by a variety of techniques; we discuss two of these techniques — jetting and drilling — below.

15.8.2.2.1 Jetted Wells

Jetted well construction commonly employs a jetting pipe with a cutting tool. This type of well cannot be constructed in clay, hardpan, or where boulders are present. Jetted wells are not acceptable as a public water supply.

15.8.2.2.2 Drilled Wells

Drilled wells are usually the only type of well allowed for use in most public water supply systems. Several different methods of drilling are available; all are capable of drilling wells of extreme depth and diameter. Drilled wells are constructed using a drilling rig that creates a hole into which the casing is placed. Screens are installed at one or more levels when water-bearing formations are encountered.

15.8.3 Components of a Well

The components that make up a well system include the well, the building and the pump, and related piping system. In this section, we focus on the components that make up the well. Many of these components are shown in Figure 15.7.

15.8.3.1 Well Casing

A well is a hole in the ground called the borehole. The hole is protected from collapse by placing a casing inside the borehole. The well casing prevents the walls of the hole from collapsing and prevents contaminants (either surface or subsurface) from entering the water source. The casing also provides a column of stored water and housing for the pump mechanisms and pipes. Well casings constructed of steel or plastic material are acceptable. The well casing must extend a minimum of 12 in. above grade.

15.8.3.2 Grout

To protect the aquifer from contamination, the casing is sealed to the borehole near the surface and near the bottom where it passes into the impermeable layer with grout. This sealing process keeps the well from being polluted by surface water and seals out water from water-bearing strata that have undesirable water quality. Sealing also protects the casing from external corrosion and restrains unstable soil and rock formations.

Grout consists of near cement that is pumped into the annular space (it is completed within 48 hours of well construction); it is pumped under continuous pressure starting at the bottom and progressing upward in one continuous operation.

15.8.3.3 Well Pad

The well pad provides a ground seal around the casing. The pad is constructed of reinforced concrete 6×6 ft (6 in. thick) with the well head located in the middle. The well pad prevents contaminants from collecting around the well and seeping down into the ground along the casing.

15.8.3.4 Sanitary Seal

To prevent contamination of the well, a sanitary seal is placed at the top of the casing. The type of seal varies depending upon the type of pump used. The sanitary seal contains openings for power and control wires, pump support cables, a drawdown gauge, discharge piping, pump shaft, and air vent, while providing a tight seal around them.

15.8.3.5 Well Screen

Screens can be installed at the intake points on the end of a well casing or on the end of the inner casing on a gravel packed well. These screens perform two functions: (1) supporting the borehole, and (2) reducing the amount of sand that enters the casing and the pump. They are sized to allow the maximum amount of water while preventing the passage of sand, sediment, or gravel.

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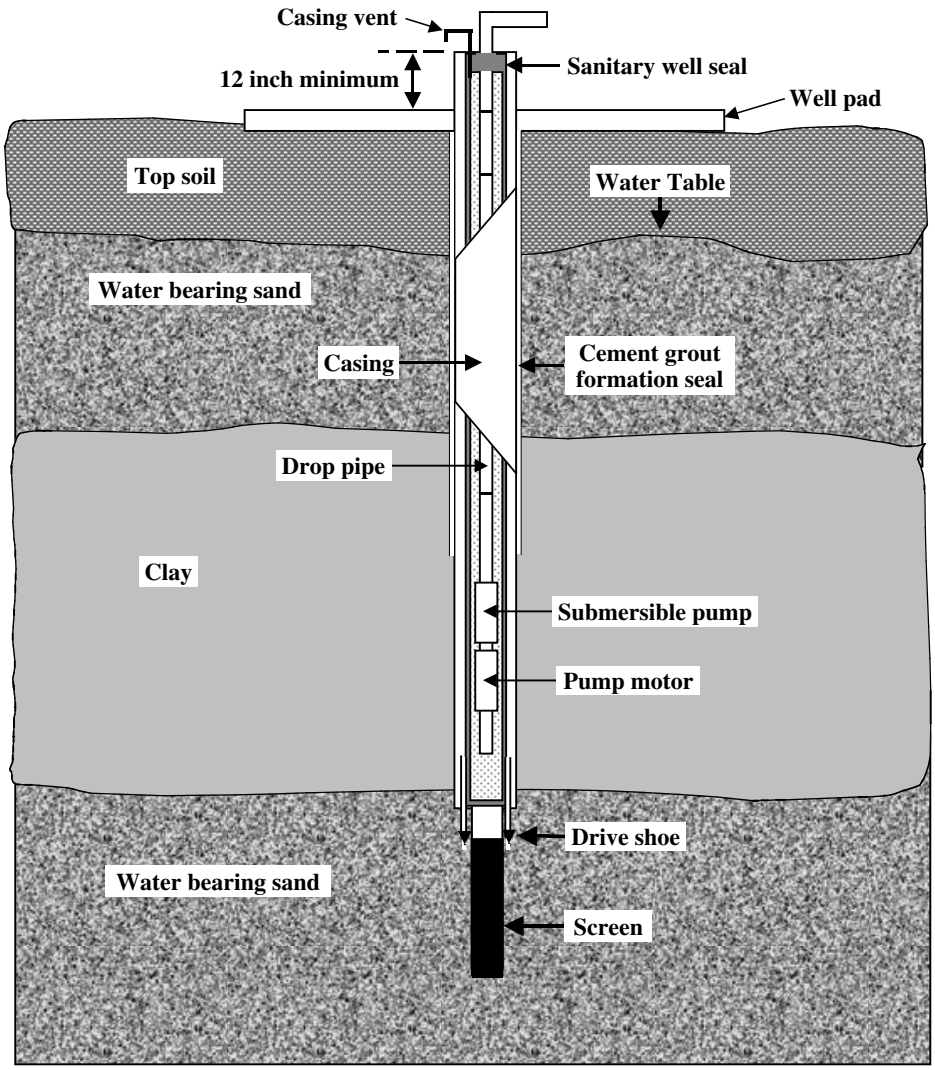

FIGURE 15.7 Components of a well. (From Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.)

15.8.3.6 Casing Vent

The well casing must have a vent to allow air into the casing as the water level drops. The vent terminates 18 in. above the floor with a return bend pointing downward. The opening of the vent must be screened with #24 mesh stainless steel to prevent entry of vermin and dust.

15.8.3.7 Drop Pipe

The drop pipe or riser is the line leading from the pump to the well head. It assures adequate support so that an aboveground pump does not move and so that a submersible pump is not lost down the well. This pipe is either steel or polyvinyl chloride. Steel is the most desirable.

15.8.3.8 Miscellaneous Well Components

Miscellaneous well components include:

Gauge and air line measures water level of the well.
Check valve located immediately after the well, it prevents system water from returning to the well. It must be located above ground and be protected from freezing.
Flowmeter required to monitor the total amount of water withdrawn from the well, including any water blown off.
Control switches controls for well pump operation.
Blowoff valved and located between the well and storage tank; used to flush the well of sediment or turbid or super-chlorinated water.

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Sample taps (a) Raw water sample tap: located before any storage or treatment to permit sampling of the water directly from the well. (b) Entry point sample tap: located after treatment.

Control valves isolates the well for testing or maintenance or used to control water flow.

15.8.4 Well Evaluation

After a well is developed, conducting a pump test determines if it can supply the required amount of water. The well is generally pumped for at least 6 h (many states require a 48-h yield and drawdown test) at a rate equal to or greater than the desired yield.

Yield is the volume or quantity of water per unit of time discharged from a well (gallons per minute, cubic feet per second). Regulations usually require that a well produce a minimum of 0.5 gal/min per residential connection.

Drawdown is the difference between the static water level (level of the water in the well when it has not been used for some time and has stabilized) and the pumping water level in a well. Drawdown is measured by using an airline and pressure gauge to monitor the water level during the 48 h of pumping.

The procedure calls for the airline to be suspended inside the casing down into the water. At the other end are the pressure gauge and a small pump. Air is pumped into the line (displacing the water) until the pressure stops increasing. The gauge's highest pressure reading is recorded.

During the 48 h of pumping, the yield and drawdown are monitored more frequently during the beginning of the testing period, because the most dramatic changes in flow and water level usually occur then.

The original static level should be recovered within 24 h after pumping stops.

Testing is accomplished on a bacteriological sample for analysis by the most potable number (MPN) method every half-hour during the last 10 h of testing. The results are used to determine if chlorination is required or if chlorination alone will be sufficient to treat the water. Chemical, physical, and radiological samples are collected for analyses at the end of the test period to determine if treatment other than chlorination may be required.

Note: Recovery from the well should be monitored at the same frequency as during the yield and drawdown testing and for at least the first 8 hours, or until 90% of the observed drawdown is obtained.

Specific capacity (often called productivity index) is a test method for determining the relative adequacy of a well, and over a period of time, is a valuable tool in evaluating well production. Specific capacity is expressed as a measure of well yield per unit of drawdown (yield divided by drawdown). When conducting this test, if possible, always run the pump for the same length of time and at the same pump rate.

15.8.5 Well Pumps

Pumps are used to move the water out of the well and deliver it to the storage tank or distribution system. The type of pump chosen for use should provide optimum performance based on location and operating conditions, required capacity, and total head.

Two types of pumps commonly installed in groundwater systems are lineshaft turbines and submersible turbines. Whichever type of pump is used, they are rated on the basis of pumping capacity expressed in gallons per minute (e.g., 40 gal/min), not on horsepower.

15.8.6 Routine Operation and Record Keeping Requirements

Ensuring the proper operation of a well requires close monitoring; wells should be visited regularly. During routine monitoring visits, check for any unusual sounds in the pump, line, or valves, and for any leaks. In addition, as a routine, cycle valves to ensure good working condition. Check motors to make sure they are not overheating. Check the well pump to guard against short cycling. Collect a water sample for a visual check for sediment. Also, check chlorine residual and treatment equipment. Measure gallons on the installed meter for 1 min to obtain pump rate in gallons per minute (look for gradual trends or big changes). Check water level in the well at least monthly (maybe more often in summer or during periods of low rainfall). Finally, from recorded meter readings, determine gallons used and compare with water consumed to determine possible distribution system leaks.

Along with meter readings, other records must be accurately and consistently maintained for water supply wells. This recordkeeping is absolutely imperative. The records (an important resource for troubleshooting) can be useful when problems develop or helpful in identifying potential problems. A properly operated and managed waterworks facility keeps the following records of well operation.

15.8.6.1 Well Log

The well log provides documentation of what materials were found in the borehole and at what depth. The well log includes the depths at which water was found, the casing length and type, the depth at which what type of soils were found, testing procedure, well development techniques, and well production. In general, the following items should be included in the well log:

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1. Well location
2. Who drilled the well
3. When the well was completed
4. Well class
5. Total depth to bedrock
6. Hole and casing size
7. Casing material and thickness
8. Screen size and locations
9. Grout depth and type
10. Yield and drawdown (test results)
11. Pump information (type, horsepower, capacity, intake depth, and model number)
12. Geology of the hole
13. A record of yield and drawdown data should be maintained.

Pump data should be collected and maintained. This data should include:

- Pump brand and model number
- Rate capacity
- Date of installation
- Maintenance performed
- Date replaced
- Pressure reading or water level when the pump will cut on and off
- Pumping time (hours per day the pump is running)
- Output in galllons per minute

A record of water quality should be kept and maintained, including bacteriological, chemical and physical (inorganic, metals, nitrate or nitrite, volatile organic compound), and radiological reports.

System-specific monthly operation reports should be kept and maintained. These reports should contain information and data from meter readings/total gallons per day/month, chlorine residuals, amount and type of chemicals used, turbidity readings, physical parameters (pH, temperature), pumping rate, total population served, and total number of connections.

A record of water level (static and dynamic levels) should be kept and maintained.

A record of any changes in conditions (such as heavy rainfall, high consumption, leaks, and earthquakes) should be kept and maintained. A record of specific capacity should also be kept and maintained.

15.8.7 Well Maintenance

Wells do not have an infinite life, and their output is likely to reduce with time as a result of hydrological and mechanical factors.

Protecting the well from possible contamination is an important consideration. If proper well location (based on knowledge of the local geological conditions and a vulnerability assessment of the area) was affected, potential problems can be minimized.

During the initial assessment, ensuring that the well is not located in a sinkhole area is important. A determination of where unconsolidated or bedrock aquifers may be subject to contamination must be made. Several other important determinations must be made. Is the well located on a floodplain? It is located next to a drainfield for septic systems or near a landfill? Are petroleum or gasoline storage tanks nearby? Is pesticide/plastic manufacturing conducted near the well site?

Along with proper well location, proper well design and construction prevent wells from acting as conduits for vertical migration of contaminants into the groundwater. Basically, the pollution potential of a well equals how well it was constructed. Contamination can occur during the drilling process, and an unsealed or unfinished well is an avenue for contamination. Any opening in the sanitary seal or break in the casing may cause contamination, as can reversal of water flow.

In routine well maintenance operations, corroded casing or screens are sometimes withdrawn and replaced, but this is difficult and not always successful. Simply constructing a new well may be cheaper.

15.8.7.1 Troubleshooting Well Problems

During operation, various problems may develop. For example, the well may pump sand or mud. When this occurs, the well screen may have collapsed or corroded, causing the screen's slot openings to become enlarged (allowing debris, sand and mud, to enter). If the well screen is not the problem, the pumping rate should be checked; the pumping rate may be too high.

Other well problems, their probable causes, and the remediation required are provided below:

1. Water is white
   a. Pump might be sucking air — reduce pump rate.
2. Water rushes backwards when pump shuts off
   a. Check valve, may be leaking
3. Decrease in well yield
   a. Check static water level. A downward trend in static water level suggests that the aquifer is becoming depleted. This could be the result of the following:
      i. Local overdraft — well spacing too close
      ii. General overdraft — pumpage exceeds recharge

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iii. Temporary decrease in recharge — dry cycles
iv. Permanent decrease in recharge — less flow in rivers
v. Check specific capacity — if it has dropped 10 to 15% take steps to determine cause; may be a result of incrustation

Note: Incrustation occurs when clogging, cementation, or stoppage of a well screen and water-bearing formation occurs. Incrustations on screens and adjacent aquifer materials result from chemical or biological reactions at the air-water interface in the well. The chief encrusting agent is calcium carbonate, which cements the gravel and sand grains together. Incrustation could also be a result of carbonates of magnesium, clays and silts, or iron bacteria. Treatment involves pulling the screen and removing incrusted material, replacing the screen, or treating the screen and water bearing formation with acids. If severe, treatment may involve rehabilitating the well.

b. Pump rate is dropping, but water level is not — probable cause is pump impairment.
c. Impellers might be worn.
d. May be a change in hydraulic head, against which the pump is working. Head may change as a result of corrosion in the pipelines, higher pressure setting, or maybe a new-elevated tank.

15.8.8 Well Abandonment

In the past, common practice was simply to walk away and forget about a well when it ran dry. Today, while dry or failing wells are still abandoned, we know that they must be abandoned with care (and not completely forgotten). An abandoned well can become a convenient (and dangerous) receptacle for wastes, contaminating the aquifer. An improperly abandoned well could also become a haven for vermin, or worse, a hazard for children.

A temporarily abandoned well must be sealed with a watertight cap or wellhead seal. The well must be maintained so that it does not become a source or channel of contamination during temporary abandonment.

When a well is permanently abandoned, all casing and screen materials may be salvaged. The well should be checked from top to bottom to assure that no obstructions interfere with plugging/sealing operations. Prior to plugging, the well should be thoroughly chlorinated. Bored wells should be completely filled with cement grout. If the well were constructed in an unconsolidated formation, it should be completely filled with cement grout or clay slurry introduced through a pipe that initially extends to the bottom of the well. As the pipe is raised, it should remain submerged in the top layers of grout as the well is filled.

Wells constructed in consolidated rock or that penetrate zones of consolidated rock can be filled with sand or gravel opposite of zones of consolidated rock. The sand or gravel fill is terminated 5 ft below the top of the consolidated rock. The remainder of the well is filled with sand-cement grout.

15.9 CHAPTER REVIEW QUESTIONS AND PROBLEMS

15.1. When water is withdrawn from a well, a _____ of _____ will develop.
15.2. How far should the well casing extend above the ground or well-house floor?
15.3. A well casing should be grouted for at least 10 ft, with the first 20 ft grouted with _____.
15.4. List three sources of drinking water.
15.5. Explain GUDISW.
15.6. What are two advantages of surface water sources?
15.7. Define hydrology.
15.8. The area inside the cone of depression is called the _____.
15.9. A spring is an example of what type of water source?
15.10. Describe the function of the bar screen at a surface water intake.

REFERENCE

1. U.S. Environmental Protection Agency, *Public Drinking Water Systems: Facts and Figures,* http://www.epa.gov/safewater/pws/factoid.html, Washington, D.C., accessed on Nov. 2, 2002.

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16 Watershed Protection

Watershed protection is one of the barriers in the multiple barrier approach to protecting source water. In fact, watershed protection is the primary barrier, the first line of defense against contamination of drinking water at its source. Ideally, under the general concept of "quality in, means quality out," a protected watershed ensures that surface runoff and inflow to the source waters occur within a pristine environment.

Protecting watersheds is not only critical to humans in ensuring their continued growth in numbers but is critical to their very survival. Simply put, protecting watersheds is a challenge that we must meet. While it is true that environmental protection programs in the U.S. have gone a long way toward improving water quality during the last quarter century, yet, many challenges remain. According to U.S. Environmental Protection Agency (EPA), as of 1994, nearly 40 percent of surveyed waters in the U.S. remain too polluted for fishing, swimming and other uses. The leading causes of impairment found in the survey include silt, sewage, disease-causing bacteria, fertilizer, toxic metals, oil and grease.*

16.1 INTRODUCTION

Water regulates population growth, influences world health and living conditions, and determines biodiversity. For thousands of years, people have tried to control the flow and quality of water. Water provided resources and a means of transportation for development in some areas. Even today, the presence or absence of water is critical in determining how we can use land.

Yet, despite this long experience in water use and water management, humans often fail to manage water well. Sound water management was pushed aside in rapid, never-ending economic development in many countries. Often, optimism about the applications of technology (e.g., dam building, wastewater treatment, or irrigation measures) exceeded concerns for, or even interest in, environmental shortcomings. Pollution was viewed as the inevitable consequence of development — the price that must be paid to achieve economic progress.

Clearly, we now have reached the stage of our development when the need for management of water systems is apparent, beneficial, and absolutely imperative. Land use and activities in the watershed directly impact raw water quality. Effective watershed management improves raw water quality, controls treatment costs, and provides additional health safeguards. Depending on goals, watershed management can be simple or complex.

This chapter discusses the need for watershed management based on a multiple barrier basis and provides a brief overview of the range of techniques and approaches that can be used to investigate the biophysical, social, and economic forces affecting water and its use.

Water utility directors are charged with providing potable water in a quantity and quality to meet the public's demand. They are also charged with providing effective management on a holistic basis of the entire water supply system; such management responsibility includes proper management of the area's watershed.

Key Point: Integrated water management means putting all of the pieces together, including considering social, environmental, and technical aspects.

16.2 CURRENT ISSUES IN WATER MANAGEMENT

Note: Much of the information provided in this section is adapted from Viessman, W., Jr., Water management issues for the nineties, *Water Resources Bulletin*, 26, 883–981, 1991.

Remarkable consensus exists among worldwide experts over the current issues confronted by waterworks managers and others. These issues include the following:

1. Water availability, requirements, and use
   a. Protection of aquatic and wetland habitat management of extreme events (droughts, floods, etc.)
   b. Excessive extractions from surface and groundwater
   c. Global climate change
   d. Safe drinking water supply
   e. Waterborne commerce
2. Water quality
   a. Coastal and ocean water quality
   b. Lake and reservoir protection and restoration
   c. Water quality protection, including effective enforcement of legislation

* U.S. EPA, *Watersheds.* Accessed at http://epa.gov/owow/watershed/framewaork/ch1.html November 2, 2002

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d. Management of point- and nonpoint-source pollution
e. Impacts on land/water/air relationships
f. Health risks

3. Water management and institutions
   a. Coordination and consistency
   b. Capturing a regional perspective
   c. Respective roles of federal and state/provincial agencies
   d. Respective roles of projects and programs
   e. Economic development philosophy that should guide planning
   f. Financing and cost sharing
   g. Information and education
   h. Appropriate levels of regulation and deregulation
   i. Water rights and permits
   j. Infrastructure
   k. Population growth
   l. Water resources planning, including:
      i. Consideration of the watershed as an integrated system
      ii. Planning as a foundation for, not a reaction to, decision making
      iii. Establishment of dynamic planning processes incorporating periodic review and redirection
      iv. Sustainability of projects beyond construction and early operation
      v. A more interactive interface between planners and the public
      vi. Identification of sources of conflict as an integral part of planning
      vii. Fairness, equity, and reciprocity between affected parties

16.3 WHAT IS A WATERSHED?

At the simplest level, we all live in a watershed — the area that drains to a common waterway, such as a lake, estuary, wetland, river, stream, or even an ocean — and our individual actions can directly affect it. More specifically, a *watershed* is a protected, reserved area, usually distant from the treatment plant, where natural or artificial lakes are used for water storage, natural sedimentation, and seasonal pretreatment, with or without disinfection. A watershed is also defined as a collecting area into which water drains. The area of land encompassed could be tiny or immense. The size of a watershed, and the direction of flow of its rivers, is determined by landforms. Watersheds are associated with surface water (usually fed by gravity) to distinguish them from groundwater (usually fed by pumping).

Note: EPA's watershed approach is to provide for an "integrated, holistic strategy for more effectively restoring and protecting aquatic ecosystems and protecting human health (e.g., drinking water supplies and fish consumption)." (U.S. EPA, Committing EPA's Water Program to Advancing the Watershed Approach, http://www.epa.gov/owow/watershed/memo.html. Accessed December 2002.)

16.4 WATER QUALITY IMPACT

Generally, for a typical river system water quality is impacted by about 60% nonpoint pollution, 21% municipal discharge, 18% industrial discharge, and about 1% sewer overflows. Of the nonpoint pollution, about 67% is from agriculture, 18% is from urban, and 15% is from other sources.

Land use directly impacts water quality. The impact of land use on water quality is clearly evident in Table 16.1.

From the waterworks operator point of view, water quality issues for nutrient contamination can be summarized quite simply:

1. Nutrients + Algae = Taste and Odor Problems
2. Nutrients + Algae + Macrophytes + Decay = Trihalomethane Precursors

16.5 WATERSHED PROTECTION AND REGULATIONS

The Clean Water Act and Safe Drinking Water Act Reauthorization addresses source water protection. Implementation of regulatory compliance requirements (with guidance provided by the U.S. Department of Health) is left up to state and local health department officials to implement.

Water protection regulations in force today not only provide guidance and regulation for watershed protection, but they also provide additional benefits for those tasked with managing drinking water utilities.

The typical drinking water utility (which provides safe drinking water to the consumer) has two choices in water pollution control: "Keep it out or take it out." The "keep it out" part pertains to watershed management; if the water supply contains contaminants, they must be removed by treatment, "take it out." Utility directors and waterworks managers are concerned with controlling treatment costs. An effective watershed management program can reduce treatment costs by reducing source water contamination. The "take it out" option is much more expensive and time consuming than keeping it out in the first place.

Proper watershed management also works to maintain consumer confidence. If the consumer is aware that the water source from the area's watershed is of the highest quality, then logically, confidence in the quality of the

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TABLE 16.1
Land Use Directly Impacts Water Quality

Source	Sediment	Nutrients	Viruses, Bacteria	Trihalomethane	Iron, Manganese
Urban	x	x	x	x	x
Agriculture	x	x	x	x	x
Logging	x	x		x	x
Industrial	x	x		x	x
Septic tanks		x	x	x	
Construction	x	x			

Source: Spellman, F.R., *The Handbook for Wastewater Operator Certification,* Technomic Publ., Lancaster, PA, 2001.

water is high. High-quality water also works directly to reduce public health risks.

16.6 A WATERSHED PROTECTION PLAN

Watershed protection begins with planning. The watershed protection plan consists of several elements and includes the need to:

1. Inventory and characterize water sources
2. Identify pollutant sources
3. Assess vulnerability of intake
4. Establish program goals
5. Develop protection strategies
6. Implement program
7. Monitor and evaluate program effectiveness

16.7 RESERVOIR MANAGEMENT PRACTICES

To ensure an adequate and safe supply of drinking water for a municipality, watershed management includes proper reservoir management practices. These practices include proper lake aeration, harvesting, dredging, and use of algicide. Water quality improvements from lake aeration include reduced iron, manganese, phosphorus, ammonia, and sulfide content. Lake aeration also reduces cost of capital and operation for water supply treatment. Algicide treatment controls algae, which in turn reduces taste and odor problems. The drawback of using algicides is that they are successful for only a brief period.

16.8 WATERSHED MANAGEMENT PRACTICES

Watershed management practices include land acquisitions, land use controls, and best management practices (BMPs). Land acquisition refers to the purchase of watershed lands — those land areas that form the watershed for a particular locality. The advantage of ownership of lands included within a particular watershed are obvious; the owner (in this case, the local utility) has better control of land use, and thus can effect protective measures for ensuring a quality water supply.

Land use controls (those measures deemed necessary to protect the watershed from contamination and/or destruction) vary from location to location. For example, land use controls may be designed to prohibit mining or other industrial activities from taking place within the watershed, for protection of the water supply.

BMPs for watershed management refer specifically to agriculture, logging, urban, and construction practices. The chief problem with best management practices is that they are nonstructural measures. They are often hard to implement because they require people to change the way they behave.

In agricultural systems, BMPs may include measures such as conservation tillage and contour plowing, confined animal facility management (contain or use waste on-site and keep animals out of waterways), and appropriate pesticide and herbicide application practices (minimize use or use alternative chemicals).

Examples of logging BMPs include construction of streamside buffer zones to protect the watercourse. Logging plans should also incorporate water quality and habitat planning.

Urban BMPs revolve around targeted categories such as reduction of impervious areas (reducing tarmac, asphalt covering, and cement covering to allow for precipitation infiltration), nonstormwater discharges, and proper disposal of residential chemicals.

The primary types of BMPs used include public education programs, inspections and enforcement, structural controls (end-of-pipe solutions that seek to treat or remove pollution that has already occurred) and preventive options that are implemented to prevent or reduce the creation of waste within a process.

Examples of construction BMPs include enforcement of stormwater pollution plans and inspections. Types of construction BMPs include erosion and sediment control (i.e., minimize clearing, stage construction, and stabilize stockpiles and finished areas) and chemical control (i.e.,

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proper storage, handling, application and covering, and isolation of materials).

16.9 CHAPTER REVIEW QUESTIONS AND PROBLEMS

16.1. Define watershed.
16.2. Another name for watershed is _____.
16.3. Explain "keep it out" and "take it out."
16.4. What is the purpose of algicide in reservoir management?
16.5. Does the acronym BMP mean?

REFERENCE

1. U.S. Environmental Protection Agency, *Watersheds,* http://epa.gov/owow/watershed/framework/ch1.html, Washington, D.C., accessed on Nov. 2, 2002.

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17 Water Treatment Operations and Unit Processes

Municipal water treatment operations and associated treatment unit processes are designed to provide reliable, high quality water service for customers, and to preserve and protect the environment for future generations.

Water management officials and treatment plant operators are tasked with exercising responsible financial management, ensuring fair rates and charges, providing responsive customer service, providing a consistent supply of safe potable water for consumption by the user, and promoting environmental responsibility.

17.1 INTRODUCTION

In this chapter, we focus on water treatment operations and the various unit processes currently used to treat raw source water before it is distributed to the user. In addition, we focus on the reasons for water treatment and the basic theories associated with individual treatment unit processes. Water treatment systems are installed to remove those materials that cause disease and create nuisances. At its simplest level, the basic goal of water treatment operations is to protect public health, with a broader goal to provide potable and palatable water. The water treatment process functions to provide water that is safe to drink and is pleasant in appearance, taste, and odor.

In this text we define water treatment as any unit process that changes or alters the chemical, physical, and bacteriological quality of water with the purpose of making it safe for human consumption and appealing to the customer. Treatment also is used to protect the water distribution system components from corrosion.

Many water treatment unit processes are commonly used today. Treatment processes used depend upon the evaluation of the nature and quality of the particular water to be treated and the desired quality of the finished water.

In water treatment unit processes employed to treat raw water, one thing is certain: as new U.S. Environmental Protection Agency (EPA) regulations take effect, many more processes will come into use in the attempt to produce water that complies with all current regulations, despite source water conditions.

Small water systems tend to use a smaller number of the wide array of unit treatment processes available. This is in part because they usually rely on groundwater as the source, and also because small water systems make many sophisticated processes impractical (i.e., too expensive to install, too expensive to operate, too sophisticated for limited operating staff). This chapter concentrates on those individual treatment unit processes usually found in conventional water treatment systems, corrosion control methods, and fluoridation. A summary of basic water treatment processes (many of which are discussed in this chapter) are presented in Table 17.1.

17.2 WATERWORKS OPERATORS

Operation of a water treatment system, no matter the size or complexity, requires operators. To perform their functions at the highest knowledge and experience level possible, operators must understand the basic principles and theories behind many complex water treatment concepts and treatment systems. Under new regulations, waterworks operators must be certified or licensed.

Although actual water treatment protocols and procedures are important, without proper implementation they are nothing more than hollow words occupying space on reams of paper. This is where the waterworks operator comes in. To successfully treat water requires skill, dedication, and vigilance. The waterworks operator must not only be highly trained and skilled, but also must be conscientious — the ultimate user demands nothing less.

The role of the waterworks operator can be succinctly stated:

1. Waterworks operators provide water that complies with state Waterworks Regulations, water that is safe to drink and ample in quantity and pressure without interruption.
2. Waterworks operators must know their facilities.
3. Waterworks operators must be familiar with bacteriology, chemistry, and hydraulics.
4. Waterworks operators must stay abreast of technological change and stay current with water supply information.

In operating a waterworks facility, waterworks operator duties include:

1. Maintaining distribution system
2. Collecting or analyzing water samples
3. Operating chemicals feed equipment
4. Keeping records

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TABLE 17.1
Basic Water Treatment Processes

Process/Step	Purpose
Screening	Removes large debris (leaves, sticks, fish) that can foul or damage plant equipment
Chemical pretreatment	Conditions the water for removal of algae and other aquatic nuisances
Presedimentation	Removes gravel, sand, silt, and other gritty materials
Microstraining	Removes algae, aquatic plants, and small debris
Chemical feed and rapid mix	Adds chemicals (coagulants, pH, adjusters, etc.) to water
Coagulation/flocculation	Converts nonsettleable or settable particles
Sedimentation	Removes settleable particles
Softening	Removes hardness-causing chemicals from water
Filtration	Removes particles of solid matter which can include biological contamination and turbidity
Disinfection	Kills disease-causing organisms
Adsorption using granular activated carbon	Removes radon and many organic chemicals such as pesticides, solvents, and trihalomethanes
Aeration	Removes volatile organic chemicals, radon H2S, and other dissolved gases; oxidizes iron and manganese
Corrosion control	Prevents scaling and corrosion
Reverse osmosis, electrodialysis	Removes nearly all inorganic contaminants
Ion exchange	Removes some inorganic contaminants including hardness-causing chemicals
Activated alumina	Removes some inorganic contamination
Oxidation filtration	Removes some inorganic contaminants (e.g., iron, manganese, radium)

Source: Adapted from American Water Works Association, *Introduction to Water Treatment,* Vol. 2, Denver, CO, 1984.

5. Operating treatment unit processes
6. Performing sanitary surveys of the water supply watershed
7. Operating a cross-connection control program

17.3 PURPOSE OF WATER TREATMENT

As mentioned, the purpose of water treatment is to condition, modify and/or remove undesirable impurities, to provide water that is safe, palatable, and acceptable to users. While this is the obvious, expected purpose of treating water, various regulations also require water treatment. Some regulations state that if the contaminants listed under the various regulations are found in excess of maximum contaminant levels (MCLs), the water must be treated to reduce the levels. If a well or spring source is surface influenced, treatment is required, regardless of the actual presence of contamination. Some impurities affect the aesthetic qualities of the water; if they exceed secondary MCLs established by EPA and the state, the water may need to be treated.

If we assume that the water source used to feed a typical water supply system is groundwater (usually the case in the U.S.), a number of common groundwater problems may require water treatment. Keep in mind that water that must be treated for any one of these problems may also exhibit several other problems. Among these other problems are:

1. Bacteriological contamination
2. Hydrogen sulfide odors
3. Hard water
4. Corrosive water
5. Iron and manganese

17.4 STAGES OF WATER TREATMENT

Earlier we stated that we focus our discussion on the conventional model of water treatment. Figure 17.1 presents the conventional model discussed in this text. Figure 17.1 clearly illustrates that water treatment is made up of various stages or unit processes combined to form one treatment system. Note that a given waterworks may contain all of the unit processes discussed in the following or any combination of them. One or more of these stages may be used to treat any one or more of the source water problems listed above. Also note that the model shown in Figure 17.1 does not necessarily apply to very small water systems. In some small systems, water treatment may consist of nothing more than removal of water via pumping from a groundwater source to storage to distribution. In some small water supply operations, disinfection may be added because it is required. The basic model shown in Figure 17.1 more than likely does not mimic the type of treatment process used in most small systems. We use it in this handbook for illustrative and instructive purposes because higher level licensure requires operators, at a minimum, to learn these processes.

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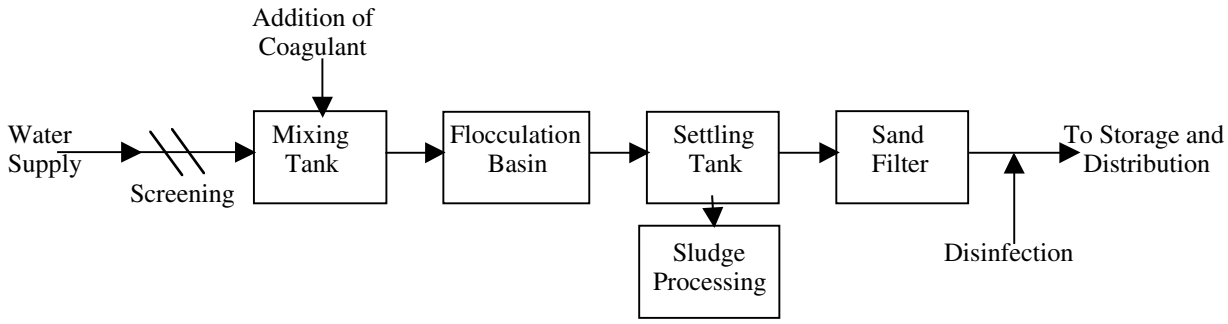

FIGURE 17.1 The conventional water treatment model. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

17.5 PRETREATMENT

Simply stated, water pretreatment (also called preliminary treatment) is any physical, chemical, or mechanical process used before main water treatment processes. It can include screening, presedimentation, and chemical addition (see Figure 17.1). Pretreatment in water treatment operations usually consists of oxidation or other treatment for the removal of tastes and odors, iron and manganese, trihalomethane (THM) precursors, or entrapped gases (like hydrogen sulfide). Unit processes may include chlorine, potassium permanganate or ozone oxidation, activated carbon addition, aeration, and presedimentation.

Pretreatment of surface water supplies accomplishes the removal of certain constituents and materials that interfere with or place an unnecessary burden on conventional water treatment facilities.

Based on our experience and according to the Texas Water Utilities Association's *Manual of Water Utility Operations*, 8th ed., typical pretreatment processes include the following:

1. Removal of debris from water from rivers and reservoirs that would clog pumping equipment.
2. Destratification of reservoirs to prevent anaerobic decomposition that could result in reducing iron and manganese from the soil to a state that would be soluble in water. This can cause subsequent removal problems in the treatment plant. The production of hydrogen sulfide and other taste- and odor-producing compounds also results from stratification.
3. Chemical treatment of reservoirs to control the growth of algae and other aquatic growths that could result in taste and odor problems.
4. Presedimentation to remove excessively heavy silt loads prior to the treatment processes.
5. Aeration to remove dissolved odor-causing gases, such as hydrogen sulfide and other dissolved gases or volatile constituents, and to aid in the oxidation of iron and manganese. (manganese or high concentrations of iron are not removed in detention provided in conventional aeration units).
6. Chemical oxidation of iron and manganese, sulfides, taste- and odor-producing compounds, and organic precursors that may produce trihalomethanes upon the addition of chlorine.
7. Adsorption for removal of tastes and odors.

Note: An important point to keep in mind is that in small systems, using groundwater as a source, pretreatment may be the only treatment process used.

Note: Pretreatment may be incorporated as part of the total treatment process or may be located adjacent to the source before the water is sent to the treatment facility.

17.5.1 Aeration

Aeration is commonly used to treat water that contains trapped gases (such as hydrogen sulfide) that can impart an unpleasant taste and odor to the water. Just allowing the water to rest in a vented tank will (sometimes) drive off much of the gas, but usually some form of forced aeration is needed. Aeration works well (about 85 percent of the sulfides may be removed) whenever the pH of the water is less than 6.5.

Aeration may also be useful in oxidizing iron and manganese, oxidizing humic substances that might form trihalomethanes when chlorinated, eliminating other sources of taste and odor, or imparting oxygen to oxygen-deficient water.

Note: Iron is a naturally occurring mineral found in many water supplies. When the concentration of iron exceeds 0.3 mg/L, red stains will occur on fixtures and clothing. This increases customer costs for cleaning and replacement of damaged fixtures and clothing.

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Manganese, like iron, is a naturally occurring mineral found in many water supplies. When the concentration of manganese exceeds 0.05 mg/L, black stains occur on fixtures and clothing. As with iron, this increases customer costs for cleaning and replacement of damaged fixtures and clothing. Iron and manganese are commonly found together in the same water supply. We discuss iron and manganese later.

17.5.2 Screening

Screening is usually the first major step in the water pretreatment process (see Figure 17.1). It is defined as the process whereby relatively large and suspended debris is removed from the water before it enters the plant. River water, for example, typically contains suspended and floating debris varying in size from small rocks to logs. Removing these solids is important, not only because these items have no place in potable water, but also because this river trash may cause damage to downstream equipment (e.g., clogging and damaging pumps, etc.), increase chemical requirements, impede hydraulic flow in open channels or pipes, or hinder the treatment process. The most important criteria used in the selection of a particular screening system for water treatment technology are the screen opening size and flow rate. Other important criteria include costs related to operation and equipment, plant hydraulics, debris handling requirements, and operator qualifications and availability.

Large surface water treatment plants may employ a variety of screening devices including rash screens (or trash rakes), traveling water screens, drum screens, bar screens, or passive screens.

17.5.3 Chemical Addition

(Note: Much of the procedural information presented in this section applies to both water and wastewater operations.)

Two of the major chemical pretreatment processes used in treating water for potable use are iron and manganese and hardness removal. Another chemical treatment process that is not necessarily part of the pretreatment process, but is also discussed in this section, is corrosion control. Corrosion prevention is effected by chemical treatment; it is not only in the treatment process, but is also in the distribution process. Before discussing each of these treatment methods in detail, it is important to describe chemical addition, chemical feeders, and chemical feeder calibration.

When chemicals are used in the pretreatment process, they must be the proper ones, fed in the proper concentration and introduced to the water at the proper locations. Determining the proper amount of chemical to use is accomplished by testing. The operator must test the raw water periodically to determine if the chemical dosage should be adjusted. For surface supplies, checking must be done more frequently than for groundwater. (Surface water supplies are subject to change on short notice, while groundwaters generally remain stable.) The operator must be aware of the potential for interactions between various chemicals and how to determine the optimum dosage (e.g., adding both chlorine and activated carbon at the same point will minimize the effectiveness of both processes, as the adsorptive power of the carbon will be used to remove the chlorine from the water).

Note: Sometimes using too many chemicals can be worse than not using enough.

Prechlorination (distinguished from chlorination used in disinfection at the end of treatment) is often used as an oxidant to help with the removal of iron and manganese. Currently, concern for systems that prechlorinate is prevalent because of the potential for the formation of total trihalomethanes (TTHMs), which form as a by-product of the reaction between chlorine and naturally occurring compounds in raw water.

Note: TTHMs such as chloroform are known or suspected to be carcinogenic and are limited by water and state regulations.

EPA's TTHM standard does not apply to water systems that serve less than 10,000 people, but operators should be aware of the impact and causes of TTHMs. Chlorine dosage or application point may be changed to reduce problems with TTHMs.

Note: To be effective, pretreatment chemicals must be thoroughly mixed with the water. Short-circuiting or plugging flows of chemicals that do not come in contact with most of the water will not result in proper treatment.

All chemicals intended for use in drinking water must meet certain standards. When ordering water treatment chemicals, the operator must be assured that they meet all appropriate standards for drinking water use.

Chemicals are normally fed with dry chemical feeders or solution (metering) pumps. Operators must be familiar with all of the adjustments needed to control the rate at which the chemical is fed to the water (wastewater). Some feeders are manually controlled and must be adjusted by the operator when the raw water quality or the flow rate changes; other feeders are paced by a flowmeter to adjust the chemical feed so it matches the water flow rate. Operators must also be familiar with chemical solution and feeder calibration.

As mentioned, a significant part of a waterworks operator's important daily operational functions includes measuring quantities of chemicals and applying them to water at preset rates. Normally accomplished semiautomatically by use of electro-mechanical-chemical feed

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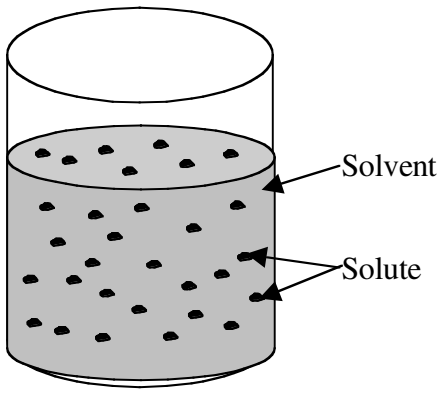

FIGURE 17.2 Solution with two components: solvent and solute. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

devices, waterworks operators must still know what chemicals to add, how much to add to the water (wastewater), and the purpose of the chemical addition.

17.5.3.1 Chemical Solutions

A water solution is a homogeneous liquid made of the solvent (the substance that dissolves another substance) and the solute (the substance that dissolves in the solvent). Water is the solvent (see Figure 17.2). The solute (whatever it may be) may dissolve up to a certain limit. This is called its solubility — the solubility of the solute in the particular solvent (water) at a particular temperature and pressure.

Note: Temperature and pressure influence stability of solutions but not by filtration. This is because only suspended material can be eliminated by filtration or by sedimentation.

Remember, in chemical solutions, the substance being dissolved is called the solute, and the liquid present in the greatest amount in a solution (that does the dissolving) is called the solvent. The operator should also be familiar with another term — concentration. This is the amount of solute dissolved in a given amount of solvent. Concentration is measured as:

$$\begin{aligned} \%\ \text{Strength} &= \frac{\text{Wt. of Solute}}{\text{Wt. of Solution}} \times 100 \\ &= \frac{\text{Wt. of Solute}}{\text{Wt. of Solute + Solvent}} \times 100 \end{aligned} \tag{17.1}$$

EXAMPLE 17.1

Problem:

If 30 lb of chemical is added to 400 lb of water, what is the percent strength (by weight) of the solution?

Solution:

$$\begin{aligned} \%\ \text{Strength} &= \frac{30\ \text{lb solute}}{400\ \text{lb H}_2\text{O}} \times 100 \\ &= \frac{30\ \text{lb solute}}{30\ \text{lb solute + 400 lb H}_2\text{O}} \times 100 \\ &= \frac{30\ \text{lb solute}}{430\ \text{lb solute/H}_2\text{O}} \times 100 \\ &= 7.0\ (\text{rounded}) \end{aligned}$$

Important to the process of making accurate computations of chemical strength is a complete understanding of the dimensional units involved. For example, operators should understand exactly what milligrams per liter signifies:

$$\text{Milligrams per Liter (mg/L)} = \frac{\text{Milligrams of Solute}}{\text{Liters of Solution}} \tag{17.2}$$

Another important dimensional unit commonly used when dealing with chemical solutions is parts per million.

$$\text{Parts per Million (ppm)} = \frac{\text{Parts of Solute}}{\text{Million Parts of Solution}} \tag{17.3}$$

Note: Parts is usually a weight measurement.

For example:

$$9\ \text{ppm} = \frac{9\ \text{lb solids}}{1{,}000{,}000\ \textit{lb solution}}$$

or

$$9\ \text{ppm} = \frac{9\ \text{mg solids}}{1{,}000{,}000\ \textit{mg solution}}$$

This leads us to two important parameters that operators should commit to memory:

Concentrations — Units and Conversions

$$1\ \text{mg/L} = 1\ \text{ppm}$$

$$1\% = 10{,}000\ \text{mg/L}$$

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When working with chemical solutions, you should also be familiar with two chemical properties we briefly described earlier: density and specific gravity. Density is defined as the weight of a substance per a unit of its volume (e.g., pounds per cubic foot or pounds per gallon). Specific gravity is defined as the ratio of the density of a substance to a standard density.

$$\text{Density} = \frac{\text{Mass of Substance}}{\text{Volume of Substance}} \tag{17.4}$$

Here are a few key facts about density (of water):

1. It is measured in units of pounds per cubic foot, pounds per gallon, or milligrams per liter.
2. The density of water is 62.5 lb/ft^3 or 8.34 lb/gal
3. Other densities include:
   A. Concrete = 130 lb/ft^3
   B. Alum (liquid, @ 60°F) = 1.33
   C. Hydrogen peroxide (35%) = 1.132

$$\text{Specific Gravity} = \frac{\text{Density of Substance}}{\text{Density of } H_2O} \tag{17.5}$$

Here are a few facts about specific gravity:

1. It has no units.
2. The specific gravity of water is 1.0
3. Other specific gravities include:
   A. Concrete = 2.08 lb/ft^3
   B. Alum (liquid, @ 60°F) = 1.33
   C. Hydrogen peroxide (35%) = 1.132

17.5.3.2 Chemical Feeders

Simply put, a chemical feeder is a mechanical device for measuring a quantity of chemical and applying it to water at a preset rate.

17.5.3.2.1 Types of Chemical Feeders

Two types of chemical feeders are commonly used: solution (or liquid) feeders and dry feeders. Liquid feeders apply chemicals in solutions or suspensions. Dry feeders apply chemicals in granular or powdered forms.

1. Solution Feeder — chemical enters feeder and leaves feeder in a liquid state.
2. Dry Feeder — chemical enters and leaves feeder in a dry state.

17.5.3.2.1.1 Solution Feeders

Solution feeders are small, positive displacement metering pumps of three types: (1) reciprocating (piston-plunger or diaphragm types), (2) vacuum type (e.g., gas chlorinator), or (3) gravity feed rotameter (e.g., drip feeder).

Positive displacement pumps are used in high pressure, low flow applications; they deliver a specific volume of liquid for each stroke of a piston or rotation of an impeller.

17.5.3.2.1.2 Dry Feeders

Two types of dry feeders are volumetric and gravimetric, depending on whether the chemical is measured by volume (volumetric-type) or weight (gravimetric-type). Simpler and less expensive than gravimetric pumps, volumetric dry feeders are also less accurate. Gravimetric dry feeders are extremely accurate, deliver high feed rates, and are more expensive than volumetric feeders.

17.5.3.3 Chemical Feeder Calibration

Chemical feeder calibration ensures effective control of the treatment process. Chemical feed without some type of metering and accounting of chemical used adversely affects the water treatment process. Chemical feeder calibration also optimizes economy of operation; it ensures the optimum use of expensive chemicals. Operators must have accurate knowledge of each individual feeder's capabilities at specific settings. When a certain dose must be administered, the operator must rely on the feeder to feed the correct amount of chemical. Proper calibration ensures chemical dosages can be set with confidence.

At a minimum, chemical feeders must be calibrated on an annual basis. During operation, when the operator changes chemical strength or chemical purity or makes any adjustment to the feeder, or when the treated water flow changes, the chemical feeder should be calibrated. Ideally, any time maintenance is performed on chemical feed equipment, calibration should be performed.

What factors affect chemical feeder calibration (i.e., feed rate)? For solution feeders, calibration is affected any time solution strength changes, any time a mechanical change is introduced in the pump (e.g., change in stroke length or stroke frequency), and whenever flow rate changes. In the dry chemical feeder, calibration is affected any time chemical purity changes, mechanical damage occurs (e.g., belt change), and whenever flow rate changes.

In the calibration process, calibration charts are usually used or made up to fit the calibration equipment. The calibration chart is also affected by certain factors, including change in chemical, change in flow rate of water being treated, and a mechanical change in the feeder.

17.5.3.3.1 Calibration Procedures

When calibrating a positive displacement pump (liquid feeder), the operator should always refer to the manufacturer's technical manual. Keeping in mind the need to refer to the manufacturer's specific guidelines, for illustrative purposes we provide examples of calibration procedures

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for simple positive displacement pump and dry feeder calibration procedures.

17.5.3.3.1.1 Calibration Procedure: Positive Displacement Pump

The following equipment is needed:

1. Graduated cylinder (1000 mL or less)
2. Stopwatch
3. Calculator
4. Graph paper
5. Plain paper
6. Straight edge

The steps for the procedure are as follows:

1. Fill graduated cylinder with solution.
2. Insert pump suction line into graduated cylinder.
3. Run pump 5 min at highest setting (100%).
4. Divide the mL of liquid withdrawn by 5 min to determine pumping rate (mL/min) and record on plain paper.
5. Repeat steps 3 and 4 at 100% setting.
6. Repeat steps 3 and 4 for 20%, 50%, and 70% settings twice.
7. Average the milliliters per minute pumped for each setting.
8. Calculate the weight of chemical pumped for each setting.
9. Calculate the dosage for each setting.
10. Graph the dosage vs. setting.

17.5.3.3.1.2 Calibration Procedure: Dry Feeder

The equipment needed for calibrating a dry chemical feeder is:

1. Weighing pan
2. Balance
3. Stopwatch
4. Plain paper
5. Graph paper
6. Straight edge
7. Calculator

The steps for the procedure are as follows:

1. Weight pan and record.
2. Set feeder at 100% setting.
3. Collect sample for 5 min.
4. Calculate weight of sample and record in table.
5. Repeat steps 3 and 4 twice.
6. Repeat steps 3 and 4 for 25%, 50%, and 75% settings twice.
7. Calculate the average sample weight per minute for each setting and record in table.
8. Calculate weight per day fed for each setting.
9. Plot weight per day vs. setting on graph paper.

Note: Pounds per day is not normally useful information for setting the feed rate setting on a feeder. This is the case because process control usually determines a dosage in parts per million, milligrams per liter, or grains per gallon. A separate chart may be necessary for another conversion based on the individual treatment facility flow rate.

To demonstrate that performing a chemical feed procedure is not necessarily as simple as opening a bag of chemicals and dumping the contents into the feed system, we provide a real-world example below.

EXAMPLE 17.2

Problem:

Consider the chlorination dosage rates below.

Setting		Dosage
100%	111/121	0.93 mg/L
70%	78/121	0.66 mg/L
50%	54/121	0.45 mg/L
20%	20/121	0.16 mg/L

Solution:

This is not a good dosage setup for a chlorination system. Maintenance of a chlorine residual at the ends of the distribution system should be within 0.5 to 1.0 ppm. At 0.9 ppm, dosage will probably result in this range, depending on the chlorine demand of the raw water and detention time in the system. However, the pump is set at its highest setting. We have room to decrease the dosage, but no ability to increase the dosage without changing the solution strength in the solution tank. In this example, doubling the solution strength to 1% provides the ideal solution, resulting in the following chart changes:

Setting		Dosage
100%	222/121	1.86 mg/L
70%	154/121	1.32 mg/L
50%	108/121	0.90 mg/L
20%	40/121	0.32 mg/L

This is ideal because the dosage we want to feed is at the 50% setting for our chlorinator. We can now easily increase or decrease the dosage whereas the previous setup only allowed the dosage to be decreased.

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17.5.3.4 Iron and Manganese Removal

Iron and manganese are frequently found in groundwater and in some surface waters. They do not cause health-related problems, but are objectionable because they may cause aesthetic problems. Severe aesthetic problems may cause consumers to avoid an otherwise safe water supply in favor of one of unknown or of questionable quality, or may cause them to incur unnecessary expense for bottled water.

Aesthetic problems associated with iron and manganese include the:

1. Discoloration of water (iron = reddish water, manganese = brown or black water)
2. Staining of plumbing fixtures
3. Impartation of a bitter taste to the water
4. Stimulation of the growth of microorganisms.

As mentioned, there are no direct health concerns associated with iron and manganese, although the growth of iron bacteria slimes may cause indirect health problems.

Economic problems include damage to textiles, dye, paper, and food. Iron residue (or tuberculation) in pipes increases pumping head and decreases carrying capacity. It may also clog pipes and corrode through them.

Note: Iron and manganese are secondary contaminants. Their secondary maximum contaminant levels (SMCLs) are = 0.3 and 0.05 mg/L, respectively.

Iron and manganese are most likely found in groundwater supplies, industrial waste, and acid mine drainage, and as by-products of pipeline corrosion. They may accumulate in lake and reservoir sediments, causing possible problems during lake or reservoir turnover. They are not usually found in running waters (e.g., streams, rivers, etc.).

17.5.3.4.1 Iron and Manganese Removal Techniques

Chemical precipitation treatments for iron and manganese removal are called deferrization and demanganization. The usual process is aeration — dissolved oxygen (DO) in the chemical causing precipitation. Chlorine or potassium permanganate may be required.

17.5.3.4.1.1 Precipitation

Precipitation (or pH adjustment) of iron and manganese from water in their solid forms can be effected in treatment plants by adjusting the pH of the water by adding lime or other chemicals. Some of the precipitate will settle out with time, while the rest is easily removed by sand filters. This process requires pH of the water to be in the range of 10 to 11.

Note: While the precipitation or pH adjustment technique for treating water containing iron and manganese is effective, note that the pH level must be adjusted higher (10 to 11 range) to cause the precipitation. This means that the pH level must then also be lowered (to the 8.5 range or a bit lower) to use the water for consumption.

17.5.3.4.1.2 Oxidation

One of the most common methods of removing iron and manganese is through the process of oxidation (another chemical process), usually followed by settling and filtration. Air, chlorine, or potassium permanganate can oxidize these minerals. Each oxidant has advantages and disadvantages, an each operates slightly differently. We discuss each oxidant in turn:

1. Air — To be effective as an oxidant, the air must come in contact with as much of the water as possible. Aeration is often accomplished by bubbling diffused air through the water by spraying the water up into the air, or by trickling the water over rocks, boards, or plastic packing materials in an aeration tower. The more finely divided the drops of water, the more oxygen comes in contact with the water and the dissolved iron and manganese.
2. Chlorine — This is one of the most popular oxidants for iron and manganese control because it is also widely used as a disinfectant; iron and manganese control by prechlorination can be as simple as adding a new chlorine feed point in a facility already feeding chlorine. It also provides a predisinfecting step that can help control bacterial growth through the rest of the treatment system. The downside to chorine use is that when chlorine reacts with the organic materials found in surface water and some groundwaters, it forms TTHMs. This process also requires that the pH of the water be in the range of 6.5 to 7. Because many groundwaters are more acidic than this, pH adjustment with lime, soda ash (Na_2CO_3), or caustic soda may be necessary when oxidizing with chlorine.
3. Potassium permanganate — This is the best oxidizing chemical to use for manganese control removal. An extremely strong oxidant, it has the additional benefit of producing manganese dioxide during the oxidation reaction. Manganese dioxide acts as an adsorbent for soluble manganese ions. This attraction for soluble manganese provides removal to extremely low levels.

The oxidized compounds form precipitates that are removed by a filter. Note that sufficient time should be allowed from the addition of the oxidant to the filtration

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step. Otherwise, the oxidation process will be completed after filtration, creating insoluble iron and manganese precipitates in the distribution system.

17.5.3.4.1.3 Ion Exchange

While the ion exchange process is used mostly to soften hard waters, it will also remove soluble iron and manganese. The water passes through a bed of resin that adsorbs undesirable ions from the water, replacing them with less troublesome ions. When the resin has given up all its donor ions, it is regenerated with strong salt brine (sodium chloride); the sodium ions from the brine replace the adsorbed ions and restore the ion exchange capabilities.

17.5.3.4.1.4 Sequestering

Sequestering or stabilization may be used when the water contains mainly low concentration of iron, and the volumes needed are relatively small. This process does not actually remove the iron or manganese from the water, but complexes (binds it chemically) it with other ions in a soluble form that is not likely to come out of solution (i.e., not likely oxidized).

17.5.3.4.1.5 Aeration

The primary physical process uses air to oxidize the iron and manganese. The water is either pumped up into the air or allowed to fall over an aeration device. The air oxidizes the iron and manganese that is then removed by use of a filter. The addition of lime to raise the pH is often added to the process. While this is called a physical process, removal is accomplished by chemical oxidation.

17.5.3.4.1.6 Potassium Permanganate Oxidation and Manganese Greensand

The continuous regeneration potassium greensand filter process is another commonly used filtration technique for iron and manganese control. Manganese greensand is a mineral (gluconite) that has been treated with alternating solutions of manganous chloride and potassium permanganate.

The result is a sand-like (zeolite) material coated with a layer of manganese dioxide — an adsorbent for soluble iron and manganese. Manganese greensand has the ability to capture (adsorb) soluble iron and manganese that may have escaped oxidation, as well as the capability of physically filtering out the particles of oxidized iron and manganese. Manganese greensand filters are generally set up as pressure filters — totally enclosed tanks containing the greensand.

The process of adsorbing soluble iron and manganese uses up the greensand by converting the manganese dioxide coating to manganic oxide, which does not have the adsorption property. The greensand can be regenerated in much the same way as ion exchange resins — by washing the sand with postassium permanganate.

17.5.3.5 Hardness Treatment

Hardness in water is caused by the presence of certain positively charged metallic irons in solution in the water. The most common of these hardness-causing ions are calcium and magnesium; others include iron, strontium, and barium.

As a general rule, groundwaters are harder than surface waters, so hardness is frequently of concern to the small water system operator. This hardness is derived from contact with soil and rock formations such as limestone. Although rainwater will not dissolve many solids, the natural carbon dioxide in the soil enters the water and forms carbonic acid (HCO), which is capable of dissolving minerals. Where soil is thick (contributing more carbon dioxide to the water) and limestone is present, hardness is likely to be a problem. The total amount of hardness in water is expressed as the sum of its calcium carbonate ($CaCO_3$) and its magnesium hardness. For practical purposes, hardness is expressed as calcium carbonate. This means that regardless of the amount of the various components that make up hardness, they can be related to a specific amount of calcium carbonate (e.g., hardness is expressed as mg/L as $CaCO_3$ — milligrams per liter as calcium carbonate).

Note: The two types of water hardness are temporary hardness and permanent hardness. Temporary hardness is also known as carbonate hardness (hardness that can be removed by boiling); permanent hardness is also known as noncarbonate hardness (hardness that cannot be removed by boiling).

Hardness is of concern in domestic water consumption because hard water increases soap consumption, leaves a soapy scum in the sink or tub, can cause water heater electrodes to burn out quickly, can cause discoloration of plumbing fixtures and utensils, and is perceived as a less desirable water. In industrial water use, hardness is a concern because it can cause boiler scale and damage to industrial equipment.

The objection of customers to hardness is often dependent on the amount of hardness they are used to. People familiar with water with a hardness of 20 mg/L might think that a hardness of 100 mg/L is too much. On the other hand, a person who has been using water with a hardness of 200 mg/L might think that 100 mg/L was very soft. Table 17.2 lists the classifications of hardness.

17.5.3.5.1 Hardness Calculation

Recall that hardness is expressed as mg/L as $CaCO_3$. The mg/L of calcium and magnesium must be converted to mg/L as $CaCO_3$ before they can be added.

The hardness (in mg/L as $CaCO_3$) for any given metallic ion is calculated using the formula:

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TABLE 17.2
Classification of Hardness

Classification	mg/L $CaCO_3$
Soft	0–75
Moderately hard	75–150
Hard	150–300
Very hard	Over 300

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

$$\text{Hardness}\left(\text{mg/L as } CaCO_3\right) = M\left(\text{mg/L}\right) \times \frac{50}{\text{Eq. Wt. of M}} = \frac{\text{Gram Molecular Weight}}{\text{Valence}} \tag{17.6}$$

where

M = metal ion concentration (mg/L)
Eq. Wt. = equivalent weight

17.5.3.5.2 Treatment Methods

Two common methods are used to reduce hardness: ion exchange and cation exchange.

17.5.3.5.2.1 Ion Exchange Process

The ion exchange process is the most frequently used process for softening water. Accomplished by charging a resin with sodium ions, the resin exchanges the sodium ions for calcium and magnesium ions. Naturally occurring and synthetic cation exchange resins are available.

Natural exchange resins include such substances as aluminum silicate, zeolite clays (Zeolites are hydrous silicates found naturally in the cavities of lavas [greensand]; glauconite zeolites; or synthetic, porous zeolites.), humus, and certain types of sediments. These resins are placed in a pressure vessel. Salt brine is flushed through the resins. The sodium ions in the salt brine attach to the resin. The resin is now said to be charged. Once charged, water is passed through the resin and the resin exchanges the sodium ions attached to the resin for calcium and magnesium ions, removing them from the water.

The zeolite clays are most common because they are quite durable, can tolerate extreme ranges in pH, and are chemically stable. They have relatively limited exchange capacities, so they should be used only for water with a moderate total hardness. One of the results is that the water may be more corrosive than before. Another concern is that addition of sodium ions to the water may increase the health risk of those with high blood pressure.

17.5.3.5.2.2 Cation Exchange Process

The cation exchange process takes place with little or no intervention from the treatment plant operator. Water containing hardness-causing cations (Ca^{++}, Mg^{++}, Fe^{+3}) is passed through a bed of cation exchange resin. The water coming through the bed contains hardness near zero, although it will have elevated sodium content. (The sodium content is not likely to be high enough to be noticeable, but it could be high enough to pose problems to people on highly restricted salt-free diets.) The total lack of hardness in the finished water is likely to make it very corrosive, so normal practice bypasses a portion of the water around the softening process. The treated and untreated waters are blended to produce an effluent with a total hardness around 50 to 75 mg/L as $CaCO_3$.

17.5.3.6 Corrosion Control

Water operators add chemicals (e.g., lime or sodium hydroxide) to water at the source or at the waterworks to control corrosion. Using chemicals to achieve slightly alkaline chemical balance prevents the water from corroding distribution pipes and consumers' plumbing. This keeps substances like lead from leaching out of plumbing and into the drinking water.

For our purpose, we define corrosion as the conversion of a metal to a salt or oxide with a loss of desirable properties such as mechanical strength. Corrosion may occur over an entire exposed surface, or may be localized at micro- or macroscopic discontinuities in metal. In all types of corrosion, a gradual decomposition of the material occurs that is often due to an electrochemical reaction. Corrosion may be caused by (1) stray current electrolysis, (2) galvanic corrosion caused by dissimilar metals, or (3) differential concentration cells. Corrosion starts at the surface of a material and moves inward.

The adverse effects of corrosion can be categorized according to health, aesthetics, economic effects, and other effects.

The corrosion of toxic metal pipe made from lead creates a serious health hazard. Lead tends to accumulate in the bones of humans and animals. Signs of lead intoxication include gastrointestinal disturbances, fatigue, anemia, and muscular paralysis. Lead is not a natural contaminant in either surface waters or groundwaters, and the MCL of 0.005 mg/L in source waters is rarely exceeded. It is corrosion by-product from high lead solder joints in copper and lead piping. Small dosages of lead can lead to developmental problems in children. The USEPA's Lead and Copper Rule addresses the matter of lead in drinking water exceeding specified action levels.

Note: EPA's Lead and Copper Rule requires that a treatment facility achieve optimum corrosion control. Since lead and copper contamination generally occurs after water has left the public

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water system, the best way for the water system operator to find out if customer water is contaminated is to test water that has come from a household faucet.

Cadmium is the only other toxic metal found in samples from plumbing systems. Cadmium is a contaminant found in zinc. Its adverse health effects are best known for being associated with severe bone and kidney syndrome in Japan. The primary maximum containment level (PMCL) for cadmium is 0.01 mg/L.

Note: Water systems should try to supply water free of lead and has no more than 1.3 mg/L of copper. This is a nonenforceable health goal.

Aesthetic effects that are a result of corrosion of iron are characterized by "pitting" and are a consequence of the deposition of ferric hydroxide and other products and the solution of iron; this is known as tuberculation. Tuberculation reduces the hydraulic capacity of the pipe. Corrosion of iron can cause customer complaints of reddish or reddish-brown staining of plumbing fixtures and laundry. Corrosion of copper lines can cause customer complaints of bluish or blue-green stains on plumbing fixtures. Sulfide corrosion of copper and iron lines can cause a blackish color in the water. The by-products of microbial activity (especially iron bacteria) can cause foul tastes and odors in the water.

The economic effects of corrosion may include the need for water main replacement, especially when tuberculation reduces the flow capacity of the main. Tuberculation increases pipe roughness, causing an increase in pumping costs and reducing distribution system pressure. Tuberculation and corrosion can cause leaks in distribution mains and household plumbing. Corrosion of household plumping may require extensive treatment, public education, and other actions under the Lead and Copper Rule.

Other effects of corrosion include short service life of household plumbing caused by pitting. The buildup of mineral deposits in the hot water system may eventually restrict hot water flow. Also the structural integrity of steel water storage tanks may deteriorate, causing structural failures. Steel ladders in clearwells or water storage tanks may corrode, introducing iron into the finished water. Steel parts in flocculation tanks, sedimentation basins, clarifiers, and filters may also corrode.

17.5.3.6.1 Types of Corrosion

Three types of corrosion occur in water mains: galvanic, tuberculation, and/or pitting:

1. Galvanic — When two dissimilar metals are in contact and are exposed to a conductive environment, a potential exists between them and current flows. This type of corrosion is the result of an electrochemical reaction when the flow of electric current is an essential part of the reaction.
2. Tuberculation — This refers to the formation of localized corrosion products scattered over the surface in the form of knob-like mounds. These mounds increase the roughness of the inside of the pipe, increasing resistance to water flow and decreasing the C-factor of the pipe.
3. Pitting — Localized corrosion is generally classified as pitting when the diameter of the cavity at the metal surface is the same or less than the depth.

17.5.3.6.2 Factors Affecting Corrosion

The primary factors affecting corrosion are pH, alkalinity, hardness (calcium), DO, and total dissolved solids. Secondary factors include temperature, velocity of water in pipes, and carbon dioxide (CO_2).

17.5.3.6.3 Determination of Corrosion Problems

To determine if corrosion is taking place in water mains, materials removed from the distribution system should be examined for signs of corrosion damage. A primary indicator of corrosion damage is pitting. (Note: Measure depth of pits to gauge the extent of damage.) Another common method used to determine if corrosion or scaling is taking place in distribution lines is by inserting special steel specimens of known weight (called coupons) in the pipe and examining them for corrosion after a period of time.

Evidence of leaks, conducting flow tests and chemical tests for DO and toxic metals, as well as customer complains (red or black water and laundry and fixture stains) are also used to indicate corrosion problems.

Formulas can also be used to determine corrosion (to an extent). The Langlier saturation index (L.I.) and aggressive index (A.I.) are two of the commonly used indices. The L.I. is a method used to determine if water is corrosive. A.I refers to waters that have low natural pH, are high in DO, are low in total dissolved solids, and have low alkalinity and low hardness. These waters are very aggressive and can be corrosive. Both L.I. and A.I. are typically used as starting points in determining the adjustments required to produce a film.

1. L.I. has a value of approximately 0.5.
2. A.I. has a value of 12 or higher.

Note: L.I and A.I. are based on the dissolving of and precipitation of calcium carbonate; therefore, the respective indices may not actually reflect the corrosive nature of the particular water for a specific pipe material. However, they can be useful tools in selecting materials or treatment options for corrosion control.

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17.5.3.6.4 Corrosion Control

As mentioned, one method used to reduce the corrosive nature of water is chemical addition. Selection of chemicals depends on the characteristics of the water, where the chemicals can be applied, how they can be applied and mixed with water, and the cost of the chemicals.

17.5.3.6.4.1 Chemical Addition: Corrosion Control Parameters

1. If the product of the calcium hardness times the alkalinity of the water is less than 100, treatment may be required. Both lime and CO_2 may be required for proper treatment of the water.
2. If the calcium hardness and alkalinity levels are between 100 and 500, either lime or Na_2CO_3 will be satisfactory. The decision regarding which chemical to use depends on the cost of the equipment and chemicals.
3. If the product of the calcium hardness times the alkalinity is greater than 500, either lime or caustic (NaOH) may be used. Soda ash will be ruled out because of the expense.
4. The chemicals chosen for treatment of public drinking water supplies modify the water characteristics, making the water less corrosive to the pipe. Modification of water quality can increase the pH of the water, reducing the hydrogen ions available for galvanic corrosion and the solubility of copper, zinc, iron, lead, and calcium. Modification of water quality also increases the possibility of forming carbonate protective films.
5. Calcium carbonate stability is the most effective means of controlling corrosion. Lime, caustic soda, or soda ash is added until the pH and the alkalinity indicates the water is saturated with calcium carbonate. Saturation does not always assure noncorrosiveness. Utilities should also exercise caution when applying sodium compounds, since high sodium content in water can be a health concern for some customers.
6. By increasing the alkalinity of the water, the bicarbonate and carbonate available to form protective carbonate film increase.
7. By decreasing the DO of the water, the rate of galvanic corrosion is reduced, along with the possibility of iron tuberculation.
8. Use of inorganic phosphates:
   A. Zinc phosphates — It is strongly recommended that this phosphate be used. It causes algae blooms on open reservoirs.
   B. Sodium silicate — Individual customers, such as apartments, houses, and office buildings use this method of treatment.
   C. Sodium polyphosphates (tetrasodium pyrophosphate or sodium hexametaphosphate) — These chemicals control scale formation in supersaturated waters and are known as sequestering agents.
   D. Silicates (SiO_2) — Silicates form a film. An initial dosage of 12 to 16 mg/L for about 30 d will adequately coat the pipes. Then 1.0 mg/L concentration should be maintained.

Caution: Great care and caution must be exercised any time feeding corrosion control chemicals into a public drinking water system.

17.5.3.6.4.2 Other Corrosion Control Methods

Another corrosion control method is *aeration.* Aeration works to remove CO_2; it can be reduced to about 5 mg/L.

Cathodic protection, often employed to control corrosion, is achieved by applying an outside electric current to the metal to reverse the electromechanical corrosion process. The application of DC current prevents normal electron flow. Cathodic protection uses a sacrificial metal electrode (a magnesium anode) that corrodes instead of the pipe or tank.

Linings, coatings, and paints can also be used in corrosion control. Slip-line with plastic liner, cement mortar, zinc or magnesium, polyethylene, epoxy, and coal tar enamels are some of the materials that can be used.

Caution: Before using any protective coatings, consult the district engineer first!

Several corrosive resistant pipe materials are used to prevent corrosion, including:

1. Polyvinyl chloride (PVC) plastic pipe
2. Aluminum
3. Nickel
4. Silicon
5. Brass
6. Bronze
7. Stainless steel
8. Reinforced concrete

In addition to internal corrosion problems, waterworks operators must also be concerned with external corrosion problems. The primary culprit involved with external corrosion of distribution system pipe is soil. The measure of corrosivity of the soil is the soil resistivity. If the soil resistivity is greater than 5000 Ω/cm, serious corrosion is unlikely. Steel pipe may be used under these conditions. If soil resistivity is less than 500 ohms/cm, plastic PVC pipe should be used. For intermediate ranges of soil resistivity (500 to 5000 Ω/cm), use ductile iron pipe, lining, and coating.

Common operating problems associated with corrosion control include:

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1. $CaCO_3$ not depositing a film — This is usually a result of poor pH control (out of the normal range of 6.5 to 8.5). This may also cause excessive film deposition.
2. Persistence of red water problems — This is most probably a result of poor flow patterns, insufficient velocity, tuberculation of pipe surface, and presence of iron bacteria.
   A. Velocity — Chemicals need to make contact with pipe surface. Dead ends and low-flow areas should have flushing program; dead ends should be looped.
   B. Tuberculation — The best approach is to clean with pig. In extreme cases, clean pipe with metal scrapers and install cement-mortar lining.
   C. Iron bacteria — Slime prevents film contact with pipe surface. Slime will grow and lose coating. Pipe cleaning and disinfection program are needed.

17.6 COAGULATION

The primary purpose in surface-water treatment is chemical clarification by coagulation and mixing, flocculation, sedimentation, and filtration. These units, processes, along with disinfection, work to remove particles, naturally occurring organic matter (NOM [i.e., bacteria, algae, zooplankton, and organic compounds]), and microbes from water. These units also help to produce water that is non-corrosive. Specifically, coagulation and flocculation work to destabilize particles and agglomerate dissolved and particulate matter. Sedimentation removes solids and provides 1/2 log giardia and 1 log virus removal. Filtration removes solids and provides 2 log giardia and 1 log virus removal. Finally, disinfection provides microbial inactivation and 1/2 giardia and 2 log Virus removal.

From Figure 17.3, it can be seen that following screening and the other pretreatment processes, the next unit process in a conventional water treatment system is a mixer where chemicals are added in what is known as coagulation. The exception to this unit process configuration occurs in small systems using groundwater, when chlorine or other taste and odor control measures are introduced at the intake and are the extent of treatment.

Materials present in raw water may vary in size, concentration, and type. Dispersed substances in the water may be classified as suspended, colloidal, or solution.

Suspended particles may vary in mass and size and are dependent on the flow of water. High flows and velocities can carry larger material. As velocities decrease, the suspended particles settle according to size and mass.

Other material may be in solution. For example, consider salt dissolving in water. Matter in the colloidal state does not dissolve, but the particles are so small they will not settle out of the water. Color (as in tea-colored swamp water) is mainly due to colloids or extremely fine particles of matter in suspension. Colloidal and solute particles in water are electrically charged. Because most of the charges are alike (negative) and repel each other, the particles stay dispersed and remain in the colloidal or soluble state.

Suspended matter will settle without treatment, if the water is still enough to allow it to settle. The rate of settling of particles can be determined, as this settling follows certain laws of physics. Much of the suspended matter may be so slow in settling that the normal settling processes become impractical, and if colloidal particles are present, settling will not occur. Moreover, water drawn from a raw water source often contains many small unstable (unsticky) particles. Therefore, sedimentation alone is usually an impractical way to obtain clear water in most locations and another method of increasing the settling rate must be used: coagulation. Simply, coagulation is designed to convert stable (unsticky) particles to unstable (sticky) particles.

The term coagulation refers to the series of chemical and mechanical operations by which coagulants are applied and made effective. These operations are comprised of two distinct phases: (1) rapid mixing to disperse coagulant chemicals by violent agitation into the water being treated and (2) flocculation to agglomerate small particles into well-defined floc by gentle agitation for a much longer time.

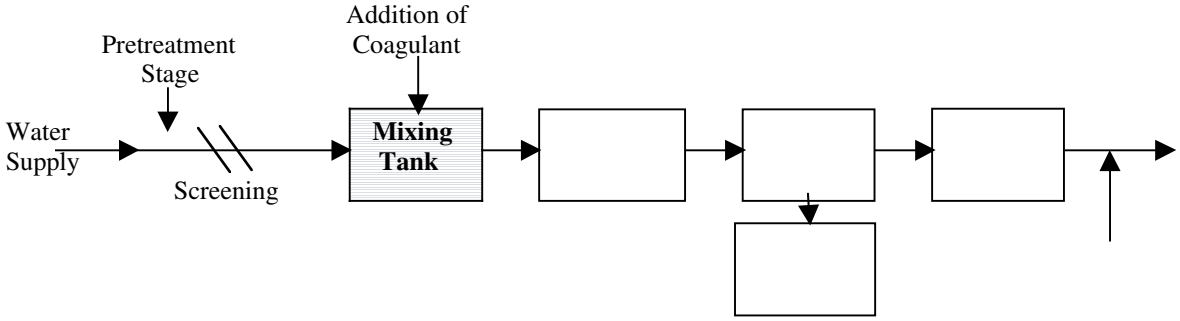

FIGURE 17.3 Coagulation. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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The coagulant must be added to the raw water and perfectly distributed into the liquid; such uniformity of chemical treatment is reached through rapid agitation or mixing.

Coagulation results from adding salts of iron or aluminum to the water. Common coagulants (salts) are as follows:

1. Alum (aluminum sulfate)
2. Sodium aluminate
3. Ferric sulfate
4. Ferrous sulfate
5. Ferric chloride
6. Polymers

Coagulation is the reaction between one of these salts and water. The simplest coagulation process occurs between alum and water. Alum or aluminum sulfate is made by a chemical reaction of bauxite ore and sulfuric acid. The normal strength of liquid alum is adjusted to 8.3%, while the strength of dry alum is 17%.

When alum is placed in water, a chemical reaction occurs that produces positively charged aluminum ions. The overall result is the reduction of electrical charges and the formation of a sticky substance — the formation of *floc,* which when properly formed, will settle. These two destabilizing factors are the major contributions that coagulation makes to the removal of turbidity, color, and microorganisms.

Liquid alum is preferred in water treatment because it has several advantages over other coagulants, including the following:

1. Ease of handling
2. Lower costs
3. Less labor required to unload, store, and convey
4. Elimination of dissolving operations
5. Less storage space required
6. Greater accuracy in measurement and control provided
7. Elimination of the nuisance and unpleasantness of handling dry alum
8. Easier maintenance

The formation of floc is the first step of coagulation; for greatest efficiency, rapid, intimate mixing of the raw water and the coagulant must occur. After mixing, the water should be slowly stirred so that the very small, newly formed particles can attract and enmesh colloidal particles, holding them together to form larger floc. This slow mixing is the second stage of the process (flocculation) and is covered later in the chapter.

A number of factors influence the coagulation process: pH, turbidity, temperature, alkalinity, and the use of polymers. The degree to which these factors influence coagulation depends upon the coagulant use.

The raw water conditions, optimum pH for coagulation, and other factors must be considered before deciding which chemical is to be fed and at what levels.

To determine the correct chemical dosage, a jar test or coagulation test is performed. Jar tests (widely used for many years by the water treatment industry) simulate full-scale coagulation and flocculation processes to determine optimum chemical dosages. It is important to note that jar testing is only an attempt to achieve a ballpark approximation of correct chemical dosage for the treatment process. The test conditions are intended to reflect the normal operation of a chemical treatment facility.

The test can be used to:

1. Select the most effective chemical.
2. Select the optimum dosage.
3. Determine the value of a flocculant aid and the proper dose.

The testing procedure requires a series of samples to be placed in testing jars (see Figure 17.4) and mixed at 100 ppm. Varying amounts of the process chemical or specified amounts of several flocculants are added (1 v/sample container). The mix is continued for 1 min. The mixing is then slowed to 30 r/min to provide gentle agitation, and the floc is allowed to settle. The flocculation period and settling process is observed carefully to determine the floc strength, settleability, and clarity of the supernatant liquor (the water that remains above the settled floc). Additionally, the supernatant can be tested to determine the efficiency of the chemical addition for removal of total suspended solids, biochemical oxygen demand, and phosphorus.

The equipment required for the jar test includes a 6-position variable speed paddle mixer (see Figure 17.4), 6 2-qt wide-mouthed jars, an interval timer, and assorted glassware, pipettes, graduates, and so forth.

17.6.1 Jar Testing Procedure

The procedure for jar testing is as follows:

1. Place an appropriate volume of water sample in each of the jars (250 to 1000 mL samples may be used, depending upon the size of the equipment being used). Start mixers and set for 100 r/min.
2. Add previously selected amounts of the chemical being evaluated. (Initial tests may use wide variations in chemical volumes to determine the approximate range. This is then narrowed in subsequent tests.)
3. Continue mixing for 1 min.

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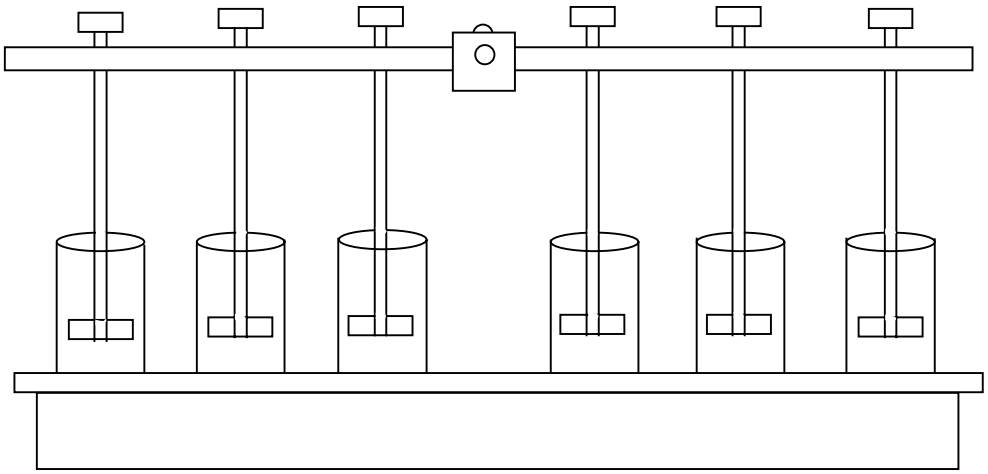

FIGURE 17.4 Variable speed paddle mixer used in jar testing procedure. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

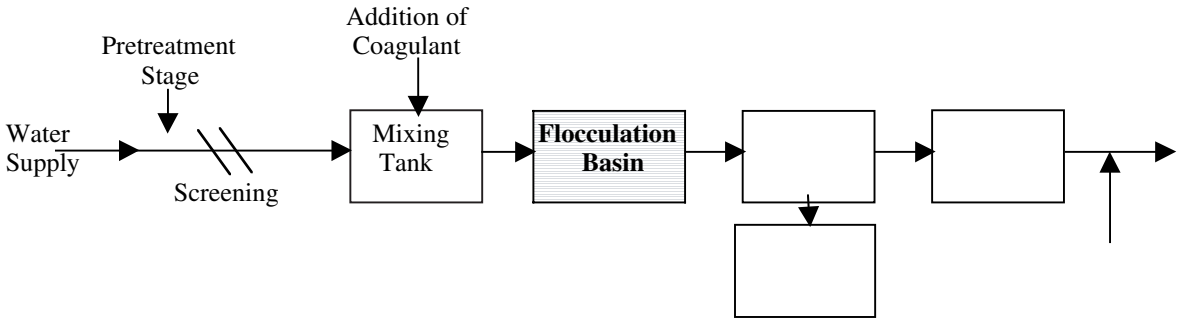

FIGURE 17.5 Flocculation. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

4. Reduce the mixer speed to a gentle agitation (30 r/min) and continue mixing for 20 min. Again, time and mixer speed may be varied to reflect the facility.

Note: During this time, observe the floc formation — how well the floc holds together during the agitation (floc strength).

5. Turn off the mixer and allow solids to settle for 20 to 30 min. Observe the settling characteristics, the clarity of the supernatant, the settleability of the solids, the flocculation of the solids, and the compactability of the solids.
6. Perform phosphate tests to determine removals.
7. Select the dose that provided the best treatment based upon the observations made during the analysis.

Note: After initial ranges and chemical selections are completed, repeat the test using a smaller range of dosages to optimize performance.

17.7 FLOCCULATION

As we see in Figure 17.5, flocculation follows coagulation in the conventional water treatment process. Flocculation is the physical process of slowly mixing the coagulated water to increase the probability of particle collision — unstable particles collide and stick together to form fewer larger flocs. Through experience, we see that effective mixing reduces the required amount of chemicals and greatly improves the sedimentation process, which results in longer filter runs and higher quality finished water.

Flocculation's goal is to form a uniform, feather-like material similar to snowflakes — a dense, tenacious floc that entraps the fine, suspended, and colloidal particles and carries them down rapidly in the settling basin.

Proper flocculation requires from 15 to 45 min. The time is based on water chemistry, water temperature, and mixing intensity. Temperature is the key component in determining the amount of time required for floc formation.

To increase the speed of floc formation and the strength and weight of the floc, polymers are often added.

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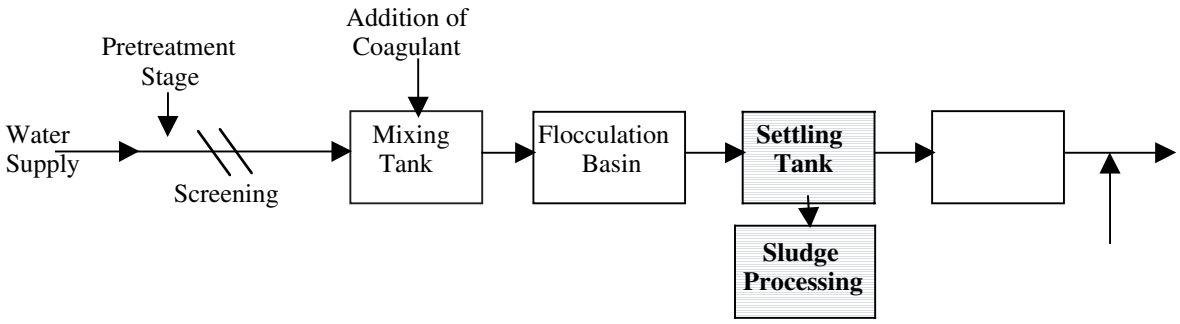

FIGURE 17.6 Sedimentation. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

17.8 SEDIMENTATION

After raw water and chemicals have been mixed and the floc formed, the water containing the floc (because it has a higher specific gravity than water) flows to the sedimentation or settling basin (see Figure 17.6).

Sedimentation is also called clarification. Sedimentation removes settleable solids by gravity. Water moves slowly though the sedimentation tank or basin with a minimum of turbulence at entry and exit points with minimum short-circuiting. Sludge accumulates at bottom of tank or basin. Typical tanks or basins used in sedimentation include conventional rectangular basins, conventional center-feed basins, peripheral-feed basins, and spiral-flow basins.

In conventional treatment plants, the amount of detention time required for settling can vary from 2 to 6 h. Detention time should be based on the total filter capacity when the filters are passing 2 gal/min/ft^2 of superficial sand area. For plants with higher filter rates, the detention time is based on a filter rate of 3 to 4 gal/min/ft^2 of sand area. The time requirement is dependent on the weight of the floc, the temperature of the water, and how quiescent (still) the basin.

A number of conditions affect sedimentation:

1. Uniformity of flow of water through the basin
2. Stratification of water due to difference in temperature between water entering and water already in the basin
3. Release of gases that may collect in small bubbles on suspended solids, causing them to rise and float as scum rather than settle as sludge
4. Disintegration of previously formed floc
5. Size and density of the floc

17.9 FILTRATION

In the conventional water treatment process, filtration usually follows coagulation, flocculation, and sedimentation (see Figure 17.7). At present, filtration is not always used in small water systems. However, recent regulatory requirements under EPA's Interim Enhanced Surface Water Treatment Rule (IESWTR) may make water filtering necessary at most water supply systems.

Water filtration is a physical process of separating suspended and colloidal particles from water by passing water through a granular material. The process of filtration involves straining, settling, and adsorption. As floc passes into the filter, the spaces between the filter grains become clogged, reducing this opening and increasing removal.

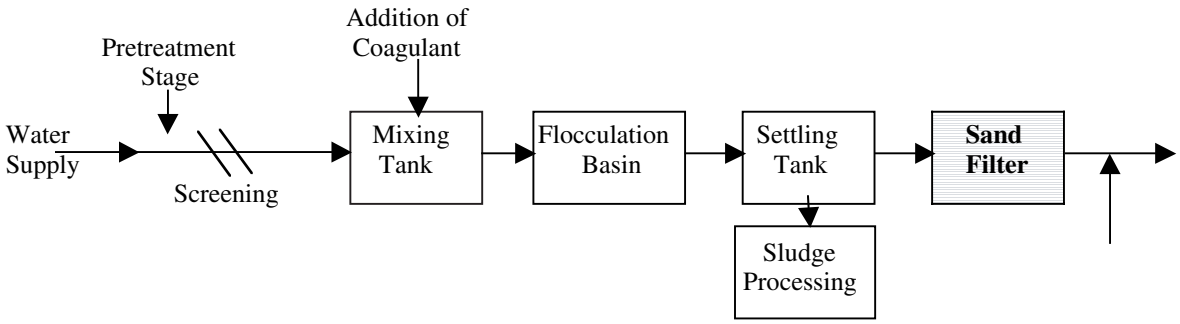

FIGURE 17.7 Filtration. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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Some material is removed merely because it settles on a media grain. One of the most important processes is adsorption of the floc onto the surface of individual filter grains. This helps collect the floc and reduces the size of the openings between the filter media grains.

In addition to removing silt and sediment, floc, algae, insect larvae, and any other large elements, filtration also contributes to the removal of bacteria and protozoans such as *Giardia lamblia* and *cryptosporidium*. Some filtration processes are also used for iron and manganese removal.

17.9.1 Types of Filter Technologies

The Surface Water Treatment Rule (SWTR) specifies four filtration technologies, although it also allows the use of alternate filtration technologies (e.g., cartridge filters). These include slow sand filtration or rapid sand filtration, pressure filtration, diatomaceous earth filtration, and direct filtration. Of these, all but rapid sand filtration are commonly employed in small water systems that use filtration. Each type of filtration system has advantages and disadvantages. Regardless of the type of filter, filtration involves the processes of straining (where particles are captured in the small spaces between filter media grains), sedimentation (where the particles land on top of the grains and stay there), and adsorption (where a chemical attraction occurs between the particles and the surface of the media grains).

17.9.1.1 Slow Sand Filters

The first slow sand filter was installed in London in 1829 and was used widely throughout Europe, though not in the U.S. By 1900, rapid sand filtration began taking over as the dominant filtration technology, and a few slow sand filters are in operation today. However, with the advent of the Safe Drinking Water Act (SDWA) and its regulations (especially the Surface Water Treatment Rule) and the recognition of the problems associated with *Giardia lamblia* and *cryptosporidium* in surface water, the water industry is reexamining slow sand filters. This is because low technology requirements may prevent many state water systems from using this type of equipment.

On the plus side, slow sand filtration is well suited for small water systems. It is a proven, effective filtration process with relatively low construction costs and low operating costs (it does not require constant operator attention). It is quite effective for water systems as large as 5000 people; beyond that, surface area requirements and manual labor required to recondition the filters make rapid sand filters more effective. The filtration rate is generally in the range of 45 to 150 gal/d/ft^2.

Components making up a slow sand filter include the following:

1. A covered structure to hold the filter media
2. An underdrain system
3. Graded rock that is placed around and just above the underdrain
4. The filter media, consisting of 30 to 55 in. of sand with a grain size of 0.25 to 0.35 mm
5. Inlet and outlet piping to convey the water to and from the filter, and the means to drain filtered water to waste

Flooding the area above the top of the sand layer with water to a depth of 3 to 5 ft and allowing it to trickle down through the sand operates slow sand filters. An overflow device prevents excessive water depth. The filter must have provisions for filling it from the bottom up. It must also be equipped with a loss-of-head gauge, a rate-of-flow control device (e.g., an orifice or butterfly valve), a weir or effluent pipe that assures that the water level cannot drop below the sand surface, and filtered waste sample taps.

When the filter is first placed in service, the head loss through the media caused by the resistance of the sand is about 0.2 ft (i.e., a layer of water 0.2 ft deep on top of the filter will provide enough pressure to push the water downward through the filter). As the filter operates, the media becomes clogged with the material being filtered out of the water, and the head loss increases. When it reaches about 4 to 5 ft, the filter needs to be cleaned.

For efficient operation of a slow sand filter, the water being filtered should have a turbidity average less than 5 turbidity units (TU), with a maximum of 30 TU.

Slow sand filters are not backwashed the way conventional filtration units are. The 1 to 2 in. of material must be removed on a periodic basis to keep the filter operating.

17.9.1.2 Rapid Sand Filters

The rapid sand filter, which is similar in some ways to slow sand filter, is one of the most widely used filtration units. The major difference is in the principle of operation — the speed or rate at which water passes through the media. In operation, water passes downward through a sand bed that removes the suspended particles. The suspended particles consist of the coagulated matter remaining in the water after sedimentation, as well as a small amount of uncoagulated suspended matter.

Some significant differences exist in construction, control, and operation between slow sand filters and rapid sand filters. Because of the construction and operation of the rapid sand filtration with its higher filtration, the land area needed to filter the same quantity of water is reduced.

The rapid sand filter structure and equipment includes the following:

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1. Structure to house media
2. Filter media
3. Gravel media support layer
4. Underdrain system
5. Valves and piping system
6. Filter backwash system
7. Waste disposal system

Usually 2 to 3 ft deep, the filter media is supported by approximately 1 ft of gravel. The media may be fine sand or a combination of sand, anthracite coal, and coal (dual-multimedia filter).

Water is applied to a rapid sand filter at a rate of 1.5 to gal/min/ft^2 of filter media surface. When the rate is between 4 and 6 gal/min/ft^2, the filter is referred to as a high-rate filter; when the rate is over gal/min/ft^2, the filter is called ultra-high-rate. These rates compare to the slow sand filtration rate of 45 to 150 gal/d/ft^2. High-rate and ultra-high-rate filters must meet additional conditions to assure proper operation.

Generally, raw water turbidity is not that high. However, even if raw water turbidity values exceed 1000 TU, properly operated rapid sand filters can produce filtered water with a turbidity or well under 0.5 TU. The time the filter is in operation between cleanings (filter runs) usually lasts from 12 to 72 h, depending on the quality of the raw water; the end of the run is indicated by the head loss approaching 6 to 8 ft. Filter breakthrough (when filtered material is pulled through the filter into the effluent) can occur if the head loss becomes too great. Operation with head loss too high can also cause air binding (which blocks part of the filter with air bubbles), increasing the flow rate through the remaining filter area.

Rapid sand filters have the advantage of lower land requirement, and have other advantages as well. For example, rapid sand filters cost less, are less labor-intensive to clean, and offer higher efficiency with highly turbid waters. On the downside, operation and maintenance costs of rapid sand filters are much higher because of the increased complexity of the filter controls and backwashing system.

In backwashing a rapid sand filter, cleaning the filter is accomplished by passing treated water backwards (upwards) through the filter media and agitating the top of the media. The need for backwashing is determined by a combination of filter run time (i.e., the length of time since the last backwashing), effluent turbidity, and head loss through the filter. Depending on the raw water quality, the run time varies from one filtration plant to another (and may even vary from one filter to another in the same plant).

Note: Backwashing usually requires 3 to 7% of the water produced by the plant.

17.9.1.3 Pressure Filter Systems

When raw water is pumped or piped from the source to a gravity filter, the head (pressure) is lost as the water enters the floc basin. When this occurs, pumping the water from the plant clearwell to the reservoir is usually necessary. One way to reduce pumping is to place the plant components into pressure vessels, maintaining the head. This type of arrangement is called a pressure filter system. Pressure filters are also quite popular for iron and manganese removal and for filtration of water from wells. They may be placed directly in the pipeline from the well or pump with little head loss. Most pressure filters operate at a rate of about 3 gal/min/ft^2.

Operationally the same as and consisting of components similar to those of a rapid sand filter, the main difference between a rapid sand filtration system and a pressure filtration system is that the entire pressure filter is contained within a pressure vessel. These units are often highly automated and are usually purchased as self-contained units with all necessary piping, controls, and equipment contained in a single unit. They are backwashed in much the same manner as the rapid sand filter.

The major advantage of the pressure filter is its low initial cost. They are usually prefabricated, with standardized designs. A major disadvantage is that the operator is unable to observe the filter in the pressure filter and determine the condition of the media. Unless the unit has an automatic shutdown feature on high effluent turbidity, driving filtered material through the filter is possible.

17.9.1.4 Diatomaceous Earth Filters

Diatomaceous earth is a white material made from the skeletal remains of diatoms. The skeletons are microscopic, and in most cases, porous. There are different grades of diatomaceous earth, and the grade is selected based on filtration requirements.

These diatoms are mixed in water slurry and fed onto a fine screen called a septum, usually of stainless steel, nylon, or plastic. The slurry is fed at a rate of 0.2 lb/ft^2 of filter area. The diatoms collect in a pre-coat over the septum, forming an extremely fine screen. Diatoms are fed continuously with the raw water, causing the buildup of a filter cake approximately 1/8 to 1/5 in. thick. The openings are so small that the fine particles that cause turbidity are trapped on the screen. Coating the septum with diatoms gives it the ability to filter out very small microscopic material. The fine screen and the buildup of filtered particles cause a high head loss through the filter. When the head loss reaches a maximum level (30 psi on a pressure-type filter or 15 inHg on a vacuum-type filter), the filter cake must be removed by backwashing.

The slurry of diatoms is fed with raw water during filtration in a process called *body feed.* The body feed

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prevents premature clogging of the septum cake. These diatoms are caught on the septum, increasing the head loss and preventing the cake from clogging too rapidly by the particles being filtered. While the body feed increases head loss, head loss increases are more gradual than if body feed were not use.

Although diatomaceous earth filters are relatively low in cost to construct, they have high operating costs and can give frequent operating problems if not properly operated and maintained. They can be used to filter raw surface waters or surface-influenced groundwaters, with low turbidity (<5 nephelometric turbidity units [NTU]), low coliform concentrations (no more than 50-coliforms/100 mL). They may also be used for iron and manganese removal following oxidation. Filtration rates are between 1.0 and 1.5 gal/min/ft^2.

17.9.1.5 Direct Filtration

The term direct filtration refers to a treatment scheme that omits the flocculation and sedimentation steps prior to filtration. Coagulant chemicals are added, and the water is passed directly onto the filter. All solids removal takes place on the filter, which can lead to much shorter filter runs, more frequent backwashing, and a greater percentage of finished water used for backwashing. The lack of a flocculation process and sedimentation basin reduces construction cost, but increases the requirement for skilled operators and high quality instrumentation. Direct filtration must be used only where the water flow rate and raw water quality are fairly consistent and where the incoming turbidity is low.

17.9.1.6 Alternate Filters

A cartridge filter system can be employed as an alternate filtering system to reduce turbidity and remove giardia. A cartridge filter is made of a synthetic media contained in a plastic or metal housing. These systems are normally installed in a series of three or four filters. Each filter contains a media that is successively smaller than the previous filter. The media sizes typically range from 50 to 5μ or less. The filter arrangement is dependent on the quality of the water, the capability of the filter, and the quantity of water needed. EPA and state agencies have established criteria for the selection and use of cartridge filters. Generally, cartridge filter systems are regulated in the same manner as other filtration systems.

Because of new regulatory requirements and the need to provide more efficient removal of pathogenic protozoa (e.g., giardia and *cryptosporidium*) from water supplies, membrane filtration systems are finding increased application in water treatment systems. A membrane is a thin film separating two different phases of a material that acts as a selective barrier to the transport of matter operated by some driving force. Simply, a membrane can be regarded as a sieve with very small pores. Membrane filtration processes are typically pressure, electrically, vacuum, or thermally driven. The types of drinking water membrane filtration systems include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. In a typical membrane filtration process, there is one input and two outputs. Membrane performance is largely a function of the properties of the materials to be separated and can vary throughout operation.

17.9.2 Common Filter Problems

Two common types of filter problems occur: (1) those caused by filter runs that are too long (infrequent backwash), and (2) those caused by inefficient backwash (cleaning).

Too long a filter run can cause breakthrough (the pushing of debris removed from the water through the media and into the effluent) and air binding (the trapping of air and other dissolved gases in the filter media).

Air binding occurs when the rate at which water exits the bottom of the filter exceeds the rate at which the water penetrates the top of the filter. When this happens, a void and partial vacuum occur inside the filter media. The vacuum causes gases to escape from the water and fill the void. When the filter is backwashed, the release of these gases may cause a violent upheaval in the media and destroy the layering of the media bed, gravel, or underdrain.

Two solutions to the problems are as follows: (1) check the filtration rates to assure they are within the design specifications, and (2) remove the top 1 in. of media and replace with new media. This keeps the top of the media from collecting the floc and sealing the entrance into the filter media.

Another common filtration problem is associated with poor backwashing practices: the formation of mud balls that get trapped in the filter media. In severe cases, mud balls can completely clog a filter. Poor agitation of the surface of the filter can form a crust on top of the filter; the crust later cracks under the water pressure, causing uneven distribution of water through the filter media. Filter cracking can be corrected by removing the top 1-in. of the filter media, increasing the backwash rate, or checking the effectiveness of the surface wash (if installed). Backwashing at too high a rate can cause the filter media to wash out of the filter over the effluent troughs and may damage the filter underdrain system.

Two possible solutions are as follows: (1) check the backwash rate to be sure that it meets the design criteria, and (2) check the surface wash (if installed) for proper operation.

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17.9.3 Filtration and Compliance with Turbidity Requirements (IESWTR)

(Note: Much of the information in this section is from EPA's *Turbidity Requirements: IESWTR Guidance Manual: Turbidity Provisions*, Washington, D.C., April 1999.)

Under the1996 SDWA Amendments, EPA must supplement the existing 1989 SWTR with the IESWTR to improve protection against waterborne pathogens. Key provisions established in the IESWTR include;[1]

1. A maximum contaminant level goal (MCLG) of zero for *cryptosporidium*; 2-log (99%) *cryptosporidium* removal requirements for systems that filter
2. Strengthened combined filter effluent turbidity performance standards
3. Individual filter turbidity monitoring provisions
4. Disinfection benchmark provisions to assure continued levels of microbial protection while facilities take the necessary steps to comply with new disinfection by-product (DBP) standards
5. Inclusion of *cryptosporidium* in the definition of groundwater under the direct influence of surface water (GWUDI) and in the watershed and in the watershed control requirements for unfiltered public water systems
6. Requirements for covers on new finished water reservoirs
7. Sanitary surveys for all surface water systems regardless of size

The following section outlines the regulatory requirements, reporting and record keeping requirements with which all waterworks operators should be familiar, and additional compliance aspects of the IESWTR related to turbidity.

17.9.3.1 Regulatory Requirements

As described above, the IESWTR contains several key provisions including strengthened combined filter effluent turbidity performance standards and individual filter turbidity monitoring.

17.9.3.1.1 Applicability

Entities potentially regulated by the IESWTR are public water systems that use surface water or GWUDI and serve at least 10,000 people (including industries, state, local, tribal, or federal governments). To determine whether your facility may be regulated by this action, you should carefully examine the applicability criteria subpart H (systems subject to the SWTR) and subpart P (subpart H systems that serve 10,000 or more people) of the final rule.

Note: Systems subject to the turbidity provisions of the IESWTR are a subset of systems subject to the IESWTR, which utilize rapid granular filtration (i.e., conventional filtration treatment and direct filtration) or other filtration processes (excluding slow sand and diatomaceous earth filtration).

17.9.3.1.2 Combined Filter Effluent Monitoring

Under the SWTR, a subpart H system that provides filtration treatment must monitor turbidity in the combined filter effluent. Turbidity measurements must be performed on representative samples of the system's filtered water every four hours (or more frequently) that the system serves water to the public. A public water system may substitute continuous turbidity monitoring for grab sample monitoring if it validates the continuous measurement for accuracy on a regular basis using a protocol approved by the State.

The turbidity performance requirements of the IESWTR require that all surface water systems that use conventional treatment or direct filtration and serve a population of 10,000 people must meet two distinct filter effluent limits: a maximum limit and a 95% limit. These limits, set forth in the IESWTR, are outlined below for the different types of treatment employed by systems.

17.9.3.1.2.1 Conventional Treatment or Direct Filtration

For conventional and direct filtration systems (including those systems utilizing in-line filtration), the turbidity level of representative samples of a system's filtered water (measured every four hours) must be less than or equal to 0.3 NTU in at least 95% of the measurements taken each month. The turbidity level of representative samples of a system's filtered water must not exceed 1 NTU at any time.

Conventional filtration is defined as a series of processes, including coagulation, flocculation, sedimentation, and filtration, resulting in substantial particulate removal. Direct filtration is defined as a series of processes, including coagulation and filtration, but excluding sedimentation, resulting in substantial particle removal.

17.9.3.1.2.2 Other Treatment Technologies (Alternative Filtration)

For other filtration technologies (those technologies other than conventional, direct, slow sand, or diatomaceous earth filtration), a system may demonstrate to the state, using pilot plant studies or other means, that the alternative filtration technology, in combination with disinfection treatment, consistently achieves 99.9 percent removal or inactivation of *Giardia lamblia* cysts and 99.99% removal or inactivation of viruses, and 99 percent removal of *cryptosporidium* oocysts. For a system that makes this demonstration, representative samples of a system's filtered water must be less than or equal to a value determined by

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the state that the state determines is indicative of 2-log *cryptosporidium* removal, 3-log giardia removal, and 4-log virus removal in at least 95% of the measurements taken each month and the turbidity level of representative samples of a system's filtered water must at no time exceed a maximum turbidity value determined by the state. Examples of such technologies include bag or cartridge filtration, microfiltration, and reverse osmosis. EPA recommends a protocol similar to the *Protocol for Equipment Verification Testing for Physical Removal of Microbiological and Particulate Contaminants* prepared by NSF International with support from EPA.

17.9.3.1.2.3 Slow Sand and Diatomaceous Earth Filtration

The IESWTR does not contain new turbidity provisions for slow sand or diatomaceous earth filtration systems. Utilities utilizing either of these filtration processes must continue to meet the requirements for their respective treatment as set forth in the SWTR (1 NTU 95%, 5 NTU max).

17.9.3.1.2.4 Systems That Utilize Lime Softening

Systems that practice lime softening may experience difficulty in meeting the turbidity performance requirements due to residual lime floc carryover inherent in the process. EPA is allowing such systems to acidify turbidity samples prior to measurement using a protocol approved by states. The chemistry supporting this decision is well-documented in environmental chemistry texts.

EPA recommends that acidification protocols lower the pH of samples to <8.3 to ensure an adequate reduction in carbonate ions and corresponding increase in bicarbonate ions. Acid should consist of either hydrochloric acid or sulfuric acid of standard lab grade. Care should be taken when adding acid to samples. Operators should always follow the sampling guidelines as directed by their supervisors and standard protocols.

If systems choose to use acidification, EPA recommends systems maintain documentation regarding the turbidity with and without acidification as well as pH values and quantity of acid added to the sample.

17.9.3.2 Individual Filter Monitoring

In addition to the combined filter effluent monitoring discussed above, those systems that use conventional treatment or direct filtration (including in-line filtration) must conduct continuous monitoring of turbidity for each individual filter using an approved method in §141.74(a) and must calibrate turbidimeters using the procedure specified by the manufacturer. Systems must record the results of individual filter monitoring every 15 min. If the individual filter is not providing water that contributes to the combined filter effluent, (i.e., it is not operating, is filtering to waste, or recycled), the system does not need to record or monitor the turbidity for that specific filter.

Note: Systems which utilize filtration other than conventional or direct filtration are not required to conduct individual filter monitoring, although EPA recommends such systems consider individual filter monitoring.

If there is a failure in continuous turbidity monitoring equipment, the system must conduct grab sampling every 4 h in lieu of continuous monitoring, but must return to 15-min monitoring no more than 5 working days following the failure of the equipment.

17.9.3.3 Reporting and Record Keeping

There are distinct reporting and record keeping requirements for the turbidity provisions of the IESWTR for both systems and states.

17.9.3.3.1 System Reporting Requirements

Under the IESWTR, systems are tasked with specific reporting requirements associated with combined filter effluent monitoring and individual filter effluent monitoring.

17.9.3.3.1.1 Combined Filter Effluent Reporting

Turbidity measurements as required by §141.173 must be reported within 10 days after the end of each month the system serves water to the public. Information that must be reported includes:

1. The total number of filtered water turbidity measurements taken during the month.
2. The number and percentage of filtered water turbidity measurements taken during the month that are less than or equal to the turbidity limits specified in §141.173.(0.3 NTU for conventional and direct and the turbidity limit established by the state for other filtration technologies).
3. The date and value of any turbidity measurements taken during the month exceed 1 NTU for systems using conventional filtration treatment or direct filtration and the maximum limit established by the state for other filtration technologies.

This reporting requirement is similar to the reporting requirement currently found under the SWTR.

17.9.3.3.1.2 Individual Filter Requirements

Systems utilizing conventional and direct filtration must report that they have conducted individual filter monitoring in accordance with the requirements of the IESWTR within 10 d after the end of each month the system serves water to the public.

Additionally, systems must report individual filter turbidity measurements within 10 d after the end of each

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month the system serves water to the public only if measurements demonstrate one of the following:

1. Any individual filter has a measured turbidity level greater than 1.0 NTU in 2 consecutive measurements taken 15 min apart. The system must report the filter number, the turbidity measurement, and the dates on which the exceedance occurred. In addition, the system must either produce a filter profile for the filter within 7 d of the exceedance (if the system is not able to identify an obvious reason for the abnormal filter performance) and report that the profile has been produced or report the obvious reason for the exceedance.
2. Any individual filter that has a measured turbidity level of greater than 0.5 NTU in 2 consecutive measurements taken 15 min apart at the end of the first 4 h of continuous filter operation after the filter has been backwashed or otherwise taken offline. The system must report the filter number, the turbidity, and the dates on which the exceedance occurred. In addition, the system must either produce a filter profile for the filter within 7 d of the exceedance (if the system is not able to identify an obvious reason for the abnormal filter performance) and report that the profile has been produced or report the obvious reason for the exceedance.
3. Any individual filter that has a measured turbidity level of greater than 1.0 NTU in 2 consecutive measurements taken 15 min apart at any time in each of 3 consecutive months. The system must report the filter number, the turbidity measurement, and the dates on which the exceedance occurred. In addition, the system shall conduct a self-assessment of the filter.
4. Any individual filter that has a measured turbidity level of greater than 2.0 NTU in 2 consecutive measurements taken 15 min apart at any time in each of 2 two consecutive months. The system must report the filter number, the turbidity measurement, and the date(s) on which the exceedance occurred. In addition, the system shall contact the state or a third party approved by the state to conduct a comprehensive performance evaluation.

17.9.3.3.2 State Reporting Requirements

Under §142.15, each state that has primary enforcement responsibility is required to submit quarterly reports to the administrator of the EPA on a schedule and in a format prescribed by the administrator that includes:

1. New violations by public water systems in the state during the previous quarter with respect to State regulations adopted to incorporate the requirements of national primary drinking water regulations.
2. New enforcement actions taken by the state during the previous quarter against public water systems with respect to state regulations adopted to incorporate the requirements of national primary drinking water standards.

Any violations or enforcement actions with respect to turbidity would be included in the quarterly report noted above. EPA has developed a state implementation guidance manual that includes additional information on State reporting requirements.

17.9.3.3.3 System Record Keeping Requirements

Systems must maintain the results of individual filter monitoring taken under §141.174 for at least 3 years. These records must be readily available for state representatives to review during sanitary surveys on other visits.

17.9.3.3.4 State Record Keeping Requirements

Records of turbidity measurements must be kept for no less than 1 year. The information retained must be set forth in a form which makes possible comparison with limits specified in §§141.71, 141.73, 141.173, and 141.175.

Records of decisions made on a system-by-system and case-by-case basis under provisions of part 141, subpart H or subpart P must be made in writing and kept by the State (this includes records regarding alternative filtration determinations). EPA has developed a state implementation guidance manual that includes additional information on state record keeping requirements.

17.9.3.4 Additional Compliance Issues

The following section outlines additional compliance issues associated with the IESWTR. These include schedule, individual filter follow-up action, notification, and variances and exemptions.

17.9.3.4.1 Schedule

The IESWTR was published on December 16, 1998, and became effective on February 16, 1999.

The SDWA requires within 24 months following the promulgation of a rule that the primacy agencies adopt any state regulations necessary to implement the rule. Under §14.13, these rules must be at least as stringent as those required by EPA. Thus, primary agencies must promulgate regulations that are at least as stringent as the IESWTR by December 17, 2000.

Beginning December 17, 2001, systems serving at least 10,000 people must meet the turbidity requirements in §141.173.

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17.9.3.4.2 Individual Filter Follow-Up Action

Based on the monitoring results obtained through continuous filter monitoring, a system may have to conduct one of the following follow-up actions due to persistently high turbidity levels at an individual filter:

1. Filter profile
2. Individual filter self assessment
3. Comprehensive performance evaluation (CPE)

These specific requirements are found in §141.175(b)(1)–(4).

17.9.3.4.2.1 Abnormal Filter Operations — Filter Profile

A filter profile must be produced if no obvious reason for abnormal filter performance can be identified. A filter profile is a graphical representation of individual filter performance based on continuous turbidity measurements or total particle counts vs. time for an entire filter run, from startup to backwash inclusively, that includes assessment of filter performance while another filter is being backwashed. The run length during this assessment should be representative of typical plant filter runs. The profile should include an explanation of the cause of any filter performance spikes during the run.

Examples of possible abnormal filter operations that may be obvious to operators include the following:

1. Outages or maintenance activities at processes within the treatment train
2. Coagulant feed pump or equipment failure
3. Filters being run at significantly higher loading rates than approved

It is important to note that while the reasons for abnormal filter operation may appear obvious, they could be masking other reasons which are more difficult to identify. These may include situations such as:

1. Distribution in filter media
2. Excessive or insufficient coagulant dosage
3. Hydraulic surges due to pump changes or other filters being brought online or offline.

Systems need to use best professional judgement and discretion when determining when to develop a filter profile. Attention at this stage will help systems avoid the other forms of follow-up action described below.

17.9.3.4.2.2 Individual Filter Self-Assessment

A system must conduct an individual filter self-assessment for any individual filter that has a measured turbidity level of greater than 1.0 NTU in 2 consecutive measurements taken 15 min apart in each of 3 consecutive months. The system must report the filter number, the turbidity measurement, and the dates on which the exceedance occurred.

17.9.3.4.2.3 Comprehensive Performance Evaluation

A system must conduct a CPE if any individual filter has a measured turbidity level of greater than 2.0 NTU in two consecutive measurements taken 15 min apart in 2 consecutive months. The system must report the filter number, the turbidity measurement, and the dates on which the exceedance occurred. The system shall contact the state or a third party approved by the state to conduct a comprehensive performance evaluation.

Note: EPA has developed a guidance document titled, *Handbook: Optimizing Water Treatment Plant Performance Using the Composite Correction Program* (EPA/625/6–91/027, revised August 1998).

17.9.3.4.3 Notification

The IESWTR contains two distinct types of notification: state and public. It is important to understand the differences and requirements between each.

17.9.3.4.3.1 State Notification

Systems are required to notify states under §141.31. Systems must report to the state within 48 h, the failure to comply with any national primary drinking water regulation. The system within 10 d of completion of each public notification required pursuant to §141.32 must submit to the state a representative copy of each type of notice distributed, published, posted, and made available to persons served by the system and the media.

The water supply system must also submit to the state (within the time stated in the request made by the state) copies of any records required to be maintained under §141.33 or copies of any documents then in existence which the state or the administrator is entitled to inspect pursuant to the authority of §1445 of the SDWA or the equivalent provisions of the state law.

17.9.3.4.3.2 Public Notification

The IESWTR specifies that the public notification requirements of the SDWA and the implementation regulations of 40 CFR §141.32 must be followed. These regulations divide public notification requirements into two tiers. These tiers are defined as follows:

1. Tier 1
   A. Failure to comply with maximum contaminant level (MCL).
   B. Failure to comply with prescribed treatment technique.
   C. Failure to comply with a variance or exemption schedule.

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2. Tier 2
   A. Failure to comply with monitoring requirements.
   B. Failure to comply with a testing procedure prescribed by a National Primary Drinking Water Regulation (NPDWR).
   C. Operating under a variance or exemption. This is not considered a violation, but public notification is required.

There are certain general requirements that all public notices must meet. All notices must provide a clear and readily understandable explanation of the violation, any potential adverse health effects, the population at risk, the steps the system is taking to correct the violation, the necessity of seeking alternate water supplies (if any), and any preventative measures the consumer should take. The notice must be conspicuous, and not contain any unduly technical language, unduly small print, or similar problems. The notice must include the telephone number of the owner or operator or designee of the public water system as a source of additional information concerning the violation where appropriate. The notice must be bi- or multilingual if appropriate.

Tier 1 Violations

In addition, the public notification rule requires that when providing notification on potential adverse health effects in Tier 1 public notices and in notices on the granting and continued existence of a variance or exemption, the owner or operator of a public water system must include certain mandatory health effects language. For violations of treatment technique requirements for filtration and disinfection, the mandatory health effects language is:

> The EPA sets drinking water standards and has determined that the presence of microbiological contaminants are a health concern at certain levels of exposure. If water is inadequately treated, microbiological contaminants in that water cause disease. Disease symptoms may include diarrhea, cramps, nausea, and possibly jaundice, and any associated headaches and fatigue. These symptoms, however, are not just associated with disease-causing organisms in drinking water, but also may be caused by a number of factors other than your drinking water. EPA has set enforceable requirements for treating drinking water to reduce the risk of these adverse health effects. Treatment such as filtering and disinfection the water removes or destroys microbiological contaminants. Drinking water which is treated to meet EPA requirements is associated with little to none of this risk and should be considered safe.

The owner or operator of a community water system must also give a copy of the most recent notice for any Tier 1 violations to all new billing units or hookups prior to or at the time service begins.

The medium for performing public notification and the time period in which notification must be sent varies with the type of violation and is specified in

§141.32. For Tier 1 violations, the owner or operator of a public water system must give notice:

1. By publication in a local daily newspaper as soon as possible but in no case later than 14 d after the violation or failure. If the area does not have a daily newspaper, then notice shall be given by publication in a weekly newspaper of general circulation in the area.
2. By either direct mail delivery or hand delivery of the notice, either by itself or with the water bill no later than 45 d after the violation or failure. The primacy agency may waive the requirement if it determines that the owner or operator has corrected the violation with 45 d.

Although the IESWTR does not specify any acute violations, the primacy agency may specify some Tier 1 violations as posing an acute risk to human health; examples might include:

1. A waterborne outbreak in an unfiltered supply
2. Turbidity of a filtered water exceeding 1.0 NTU at any time
3. Failure to maintain a disinfectant residual of at least 0.2 mg/L in the water being delivered to the distribution system.

For these violations or any others defined by the primacy agency as acute violations, the system must furnish a copy of the notice to the radio and television stations serving the area as soon as possible but in no case later than 72 h after the violation. Depending on the circumstances particular to the system, as determined by the primacy agency, the notice may instruct that all water be boiled prior to consumption.

Following the initial notice, the owner or operator must give notice at least once every 3 months by mail delivery (either or with the water bill), or by hand delivery, for as long as the violation or failures exist.

There are two variations on these requirements. First, the owner or operator of a community water system in an area not served by a daily or weekly newspaper must give notice within 14 d after the violation by hand delivery or continuous posting of a notice of the violation. The notice must continue for as long as the violation exists. Notice by hand delivery must be repeated at least every 3 months for the duration of the violation.

Secondly, the owner or operator of a noncommunity water system (i.e., one serving a transitory population) may give notice by hand delivery or continuous posting of the notice in conspicuous places in the area served by the system. Notice must be given within 14 d after the

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violation. If notice is given by posting, then it must continue as long as the violations exist. Notice given by hand delivery must be repeated at least every 3 months for as long as the violation exists.

Tier 2 Violations

For Tier 2 violations (i.e., violations of 40 CFR §§141.74 and 141.174), notice must be given within 3 months after the violation by publication in a daily newspaper of general circulation, or if there is no daily newspaper, then in a weekly newspaper. In addition, the owner or operator shall give notice by mail (either by itself or with the water bill) or by hand delivery at least once every 3 months for as long as the violation exists. Notice of a variance or exemption must be given every 3 months from the date it is granted for as long as it remains in effect.

If a daily or weekly newspaper does not serve the area, the owner or operator of a community water system must give notice by continuous posting in conspicuous places in the area served by the system. This must continue as long as the violation exists or the variance or exemption remains in effect. Notice by hand delivery must be repeated at least every 3 months for the duration of the violation or the variance or exemption.

For noncommunity water systems, the owner or operator may give notice by hand delivery or continuous posting in conspicuous places, beginning within 3 months of the violation or the variance or exemption. Posting must continue for the duration of the violation or variance or exemption, and notice by hand delivery must be repeated at least every 3 months during this period.

The primacy agency may allow for owner or operator to provide less frequent notice for minor monitoring violations (as defined, by the primacy agency if EPA has approved the primacy agency's substitute requirements contained in a program revision application).

17.9.3.4.4 Variances and Exemptions

As with the SWTR, no variances from the requirements in §141 are permitted for subpart H systems.

Under §1416(a), EPA or a state may exempt a public water system from any requirements related to an MCL or treatment technique of an NPDWR if it finds that:

1. Due to compelling factors (which may include economic factors such as qualifications of the public water system [PWS] as serving a disadvantaged community), the PWS is unable to comply with the requirement or implement measures to develop an alternative source of water supply.
2. The exemption will not result in an unreasonable risk to health.
3. The PWS was in operation on the effective date of the NPDWR, or for a system that was not in operation by that date, only if no reasonable alternative source of drinking water is available to the new systems.
4. Management or restructuring changes (or both) cannot reasonably result in compliance with the act or improve the quality of drinking water.

17.10 DISINFECTION

(Note: Disinfection is a unit process used both in water and wastewater treatment. Many of the terms, practices, and applications discussed in this section apply to both water and wastewater treatment. There are also some differences — mainly in the types of disinfectants used and applications — between the use of disinfection in water and wastewater treatment. In this section we discuss disinfection as it applies to water treatment. Later we cover disinfection as it applies to wastewater treatment. Much of the information presented in this section is based on personal experience and on EPA's guidance manual *Alternative Disinfectants and Oxidants*, Chapters 1 and 2, Washington, D.C., April 1999.)

To comply with the SDWA regulations, the majority of PWSs use some form of water treatment. The 1995 Community Water System Survey reports that in the U.S., 99% of surface water systems provide some treatment to their water, with 99% of these treatment systems using disinfection and oxidation as part of the treatment process. Although 45% of groundwater systems provide no treatment, 92% of those groundwater plants that do provide some form of treatment include disinfection and oxidation as part of the treatment process.[2] In regards to groundwater supplies, why the public health concern? According to EPA's Bruce Macler [in What is the Ground Water Disinfection Rule [www.groc.org/winter96/gwdr.htm]):

> There are legitimate concerns for public health from microbial contamination of groundwater systems. Microorganisms and other evidence of fecal contamination have been detected in a large number of wells tested, even those wells that had been previously judged not vulnerable to such contamination. The scientific community believes that microbial contamination of groundwater is real and widespread. Public health impact from this contamination while not well quantified, appears to be large. Disease outbreaks have occurred in many groundwater systems. Risk estimates suggest several million illnesses each year. Additional research is underway to better characterize the nature and magnitude of the public health problem.

The most commonly used disinfectants and oxidants (in no particular order) are chlorine, chlorine dioxide, chloramines, ozone, and potassium permanganate.

As mentioned, the process used to control waterborne pathogenic organisms and prevent waterborne disease is called disinfection. The goal in proper disinfection in a water system is to destroy all disease-causing organisms.

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Disinfection should not be confused with sterilization. Sterilization is the complete killing of all living organisms. Waterworks operators disinfect by destroying organisms that might be dangerous; they do not attempt to sterilize water.

Disinfectants are also used to achieve other specific objectives in drinking water treatment. These other objectives include nuisance control (e.g., for zebra mussels and Asiatic clams), oxidation of specific compounds (i.e., taste and odor causing compounds, iron, and manganese), and use as a coagulant and filtration aid.

The purpose of this section is to:

1. Provide a brief overview of the need for disinfection in water treatment.
2. Provide basic information that is common to all disinfectants.
3. Discuss other uses for disinfectant chemicals (i.e., as oxidants).
4. Describe trends in DBP formation and the health effects of DBPs found in water treatment.
5. Discuss microorganisms of concern in water systems, their associated health impact, and the inactivation mechanisms and efficiencies of various disinfectants.
6. Summarize current disinfection practices in the U.S., including the use of chlorine as a disinfectant and an oxidant.

In water treatment, disinfection is almost always accomplished by adding chlorine or chlorine compounds after all other treatment steps (see Figure 17.8). However, in the U.S., ultraviolet (UV) light and potassium permanganate and ozone processes may be encountered.

The effectiveness of disinfection in a drinking water system is measured by testing for the presence or absence of coliform bacteria.

Coliform bacteria found in water are generally not pathogenic, although they are good indicators of contamination. Their presence indicates the possibility of contamination. Their absence indicates the possibility that the water is potable — if the source is adequate, the waterworks history is good, and an acceptable chlorine residual is present.

Desired characteristics of a disinfectant include the following:

1. It must be able to deactivate or destroy any type or number of disease-causing microorganisms that may be in a water supply, in reasonable time, within expected temperature ranges, and despite changes in the character of the water (e.g., pH).
2. It must be nontoxic.
3. It must not add unpleasant taste or odor to the water.
4. It must be readily available at a reasonable cost and be safe and easy to handle, transport, store, and apply.
5. It must be quick and easy to determine the concentration of the disinfectant in the treated water.
6. It should persist within the disinfected water at a high enough concentration to provide residual protection through the distribution.

17.10.1 Need for Disinfection in Water Treatment

Although the epidemiological relation between water and disease had been suggested as early as the 1850s, it was not until the establishment of the germ theory of disease by Louis Pasteur in the mid-1880s that water as a carrier of disease-producing organisms was understood. In the 1850s, while London experienced the Broad Street Well cholera epidemic, Dr. John Snow conducted his now famous epidemiological study. Dr. Snow concluded that the well had become contaminated by a visitor with the disease, who had arrived in the vicinity. Cholera was one of the first diseases to be recognized as capable of being waterborne. Also, this incident was probably the first reported disease epidemic attributed to direct recycling of

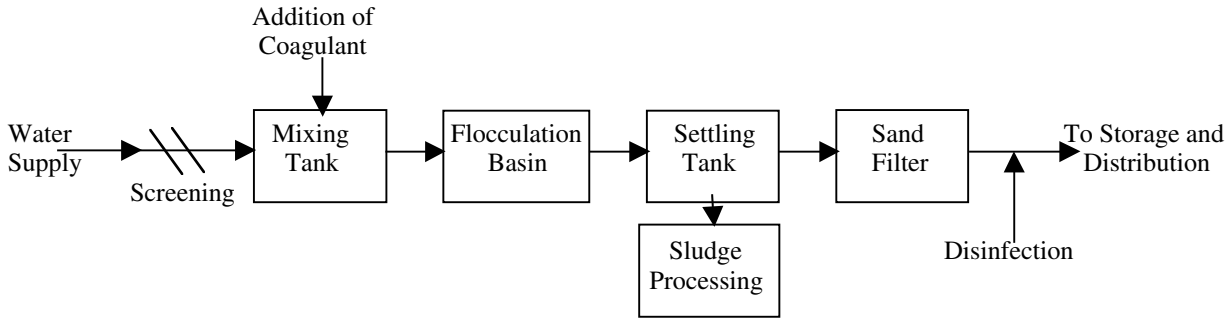

FIGURE 17.8 Disinfection. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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TABLE 17.3
Waterborne Diseases from Bacteria

Causative Agent	Disease
Salmonella typhosa	Typhoid fever
S. paratyphi	Paratyphoid fever
S. schottinulleri	
S. hirschfeldi C.	
Shigella flexneri	Bacillary dysentery
Sh. dysenteriae	
Sh. sonnel	
Sh. paradysinteriae	
Vibrio comma	Cholera
V. cholerae	
Pasteurella tularensis	Tularemia
Brucella melitensis	Brucellosis
Leptospira icterchaemorrihagiae	Leptospirosis
Enteropathogenic E. coli	Gastroenteritis

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

TABLE 17.4
Waterborne Diseases from Human Enteric Viruses

Group	Subgroup
Enterovirus	Poliovirus
Reovirus	Echovirus
Adenovirus	Coxsackie-virus (type A or B)
Hepatitis	

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

nondisinfected water. Now, over 100 years later, the list of potential waterborne disease due to pathogens is considerably larger. It includes bacterial, viral, and parasitic microorganisms, as shown in Table 17.3, Table 17.4, and Table 17.5, respectively.

A major cause for the number of disease outbreaks in potable water is contamination of the distribution system from cross connections and back siphonage with non-potable water. However, outbreaks resulting from distribution system contamination are usually quickly contained and result in relatively few illnesses compared to contamination of the source water or a breakdown in the treatment system, which typically produce many cases of illnesses per incident. When considering the number of cases, the

TABLE 17.5
Waterborne Diseases from Parasites

Causative Agent	Symptoms
Ascario lumbricoides (round worm)	Ascariasis
Cryptosporidium muris and *parvum*	Cryptosporidiosis
Entamoeba histolytica	Amebiasis
Giardia lamblia	Giardiasis
Naegleria gruberi	Amoebic meningoecephalitis
Schistosoma mansoni	Schistosomiasis
Taenis saginata (beef tapeworm)	Taeniasis

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

major causes of disease outbreaks are source water contamination and treatment deficiencies.[3] Historically, about 46% of the outbreaks in the public water systems are found to be related to deficiencies in source water and treatment systems, with 92% of the causes of illness due to these two particular problems.

All natural waters support biological communities. Because some microorganisms can be responsible for public health problems, biological characteristics of the source water are one of the most important parameters in water treatment. In addition to public health problems, microbiology can also affect the physical and chemical water quality and treatment plant operation.

17.10.2 Pathogens of Primary Concern

Table 17.6 shows the attributes of three groups of pathogens of concern in water treatment: bacteria, viruses, and protozoa.

17.10.2.1 Bacteria

Recall that bacteria are single-celled organisms typically ranging in size from 0.1 to 10 μm. Shape, components, size, and the manner in which they grow can characterize the physical structure of the bacterial cell. Most bacteria can be grouped by shape into four general categories: spheroid, rod, curved rod or spiral, and filamentous. Cocci, or spherical bacteria, are approximately 1 to 3 μm in diameter. Bacilli (rod-shaped bacteria) are variable in size and range from 0.3 to 1.5 μm in width (or diameter) and from 1.0 to 10.0 μm in length. Vibrios, or curved rod-shaped bacteria, typically vary in size from 0.6 to 1.0 μm in width (or diameter) and from 2 to 6 μm in length. Spirilla (spiral bacteria) can be found in lengths up to 50 μm whereas filamentous bacteria can occur in length in excess of 100 μm.

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TABLE 17.6
Attributes of the Three Waterborne Pathogens in Water Treatment

Organism	Size (μm)	Mobility	Points of Origin	Resistance to Disinfection
Bacteria	0.1–10	Motile; nonmotile	Humans and animals; water; contaminated food	Type specific-bacterial spores typically have the highest resistance whereas vegetative bacteria have the lowest resistance
Viruses	0.0–0.01	Nonmotile	Humans and animals; polluted water; contaminated food	Generally more resistant than vegetative bacteria
Protozoa	1–28	Motile; nonmotile	Humans and animals; sewage; decaying vegetation; water	More resistant than viruses or vegetative bacteria

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

TABLE 17.7
Human Parasitic Protozoa

Protozoan	Hosts	Disease	Transmission
Acanathamoeba castellannii	Fresh water; sewage; humans; soil	Amoebic meningoencephalitis	Gains entry through abrasions, ulcers, and as secondary invader during other infections
Balantidium coli	Pigs; humans	Balantidiasis (dysentery)	Contaminated water
Cryptosporidium parvum	Animals; humans	Cryptosporidiosis	Person-to-person or animal-to-person contact; ingestion of fecally contaminated water or food; contact with fecally contaminated environmental surfaces
Entamoeba histolytica	Humans	Amoebic dysentery	Contaminated water
Giardia lamblia	Animals; humans	Giardiasis (gastroenteritis)	Contaminated water
Naegleria fowleri	Soil; water; humans; decaying vegetation	Primary amoebic meningoencephalitis	Nasal inhalation with subsequent penetration of nasopharynx; exposure of swimming in freshwater lakes

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

17.10.2.2 Viruses

As mentioned earlier, viruses are microorganisms composed of the genetic material deoxyribonucleic acid (DNA) or ribonucleic acid (RNA) and a protective protein coat (single, double, or partially double stranded). All viruses are obligate parasites, unable to carry out any form of metabolism, and are completely dependent upon host cells for replication. Viruses are typically 0.01 to 0.1 μm in size and are very species specific with respect to infection, typically attacking only one type of host. Although the principal modes of transmission for the hepatitis B virus and poliovirus are through food, personal contact, or exchange of body fluids, these viruses can be transmitted through potable water. Some viruses, such as the retroviruses (including HIV group), appear to be too fragile for water transmission to be a significant danger to public health.[4]

17.10.2.3 Protozoa

Recall that protozoa are single-cell eukaryotic microorganisms without cell walls that utilize bacteria and other organisms for food. Most protozoa are free-living in nature and can be encountered in water; however, several species are parasitic and live on or in host organisms. Host organisms can vary from primitive organism such as algae to highly complex organisms such as human beings. Several species of protozoa known to utilize human beings as hosts are shown in Table 17.7.

17.10.3 Recent Waterborne Outbreaks

Within the past 40 years, several pathogenic agents never before associated with documented waterborne outbreaks have appeared in the U.S. Enteropathogenic *E. Coli* and *Giardia lamblia* were first identified to be the etiological agent responsible for waterborne outbreaks in the 1960s.The first recorded *cryptosporidium* infection in humans occurred in the mid-1970s. Also during that time was the first recorded outbreak of pneumonia caused by *Legionella pneumophila*.[5] Recently, there have been numerous documented waterborne disease outbreaks that have been caused by *E. coli*, *Giardia lamblia*, *cryptosporidium*, and *Legionella pneumophila.*

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17.10.3.1 *E. coli*

The first documented case of waterborne disease outbreaks in the U.S. associated with enteropathogenic *E. coli* occurred in the 1960s. Various serotypes of *E. coli* have been implicated as the etiological agent responsible for disease in newborn infants, usually the result of cross contamination in nurseries. Now, there have been several well-documented outbreaks of *E. coli* associated with adult waterborne disease.[6] In 1975, the etiologic agent of a large outbreak at Crater Lake National Park was *E. coli* serotype 06:H16.[7]

17.10.3.2 *Giardia lamblia*

Similar to *E. coli*, *Giardia lamblia* was first identified in the 1960s to be associated with waterborne outbreaks in the United States. Recall that *Giardia lamblia* is a flagellated protozoan that is responsible for giardiasis, a disease that can range from being mildly to extremely debilitating. Giardia is currently one of the most commonly identified pathogens responsible for waterborne disease outbreaks. The life cycle of giardia includes a cyst stage when the organism remains dormant and is extremely resilient (i.e., the cyst can survive some extreme environmental conditions). Once ingested by a warm-blooded animal, the life cycle of giardia continues with excystation. The cysts are relatively large (8 to 14 μm) and can be removed effectively by filtration using diatomaceous earth, granular media, or membranes.

Giardiasis can be acquired by ingesting viable cysts from food or water or by direct contact with fecal material. In addition to humans, wild and domestic animals have been implicated as hosts. Between 1972 and 1981, 50 waterborne outbreaks of giardiasis occurred with about 20,000 reported cases.[8] Currently, no simple and reliable method exists to assay Giardia cysts in water samples. Microscopic methods for detection and enumeration are tedious and require examiner skill and patience. Giardia cysts are relatively resistant to chlorine, especially at higher pH and low temperatures.

17.10.3.3 *Cryptosporidium*

Cryptosporidium is a protozoan similar to giardia. It forms resilient oocysts as part of its life cycle. The oocysts are smaller than giardia cysts, typically about 4 to 6 μm in diameter. These oocysts can survive under adverse conditions until ingested by a warm-blooded animal and then continue with excystation.

Due to the increase in the number of outbreaks of cryptosporidiosis, a tremendous amount of research has focused on *cryptosporidium* within the last 10 years. Medical interest has increased because of its occurrence as a life-threatening infection to individuals with depressed immune systems. As previously mentioned, in 1993, the largest documented waterborne disease outbreak in U.S. occurred in Milwaukee and was determined to be caused by *cryptosporidium*. An estimated 403,000 people became ill, 4,400 people were hospitalized, and 100 people died. The outbreak was associated with deterioration in raw water quality and a simultaneous decrease in effectiveness of the coagulation-filtration process; this process led to an increase in the turbidity of treated water and inadequate removal of *cryptosporidium* oocysts.

17.10.3.4 *Legionella pneumophila*

An outbreak of pneumonia occurred in 1976 at the annual convention of the Pennsylvania American Legion. A total of 221 people were affected by the outbreak, and 35 of those afflicted died. The cause of pneumonia was not determined immediately despite an intense investigation by the Centers for Disease Control. Six months after the incident, microbiologists were able to isolate a bacterium from the autopsy lung tissue of one of the legionnaires. The bacterium responsible to the outbreak was found to be distinct from other known bacterium and was named *Legionella pneumophila.*[9]

Following the discovery of this organism, other legionella-like organisms were discovered. Altogether, 26 species of *Legionella* have been identified, and 7 are etiologic agents for Legionnaires' disease.[10]

Legionnaires' disease does not appear to be transferred person-to-person. Epidemiological studies have shown that the disease enters the body through the respiratory system. Legionella can be inhaled in water particles less than 5 μm in size from facilities such as cooling towers, hospital hot water systems, and recreational whirlpools.[9]

17.10.4 Mechanism of Pathogen Inactivation

The three primary mechanisms of pathogen inactivation are to:

1. Destroy or impair cellular structural organization by attacking major cell constituents, such as destroying the cell wall or impairing the functions of semipermeable membranes.
2. Interfere with energy-yielding metabolism through enzyme substrates in combination with prosthetic groups of enzymes, rendering them nonfunctional.
3. Interfere with biosynthesis and growth by preventing synthesis of normal proteins, nucleic acids, coenzymes, or the cell wall.

Depending on the disinfectant and microorganism type, combinations of these mechanisms can also be responsible for pathogen inactivation. In water treatment, it is believed that the primary factors controlling disinfection efficiency are: (1) the ability of the disinfectant to

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oxidize or rupture the cell wall, and (2) the ability of the disinfectant to diffuse into the cell and interfere with cellular activity.[11]

In addition, it is important to point out that disinfection is effective in reducing waterborne diseases because most pathogenic organisms are more sensitive to disinfection than are nonpathogens. Disinfection is only as effective as the care used in controlling the process and assuring that all of the water supply is continually treated with the amount of disinfectant required producing safe water.

17.10.5 Other Uses of Disinfectants in Water Treatment

Disinfectants are used for more than just disinfection in drinking water treatment. While inactivation of pathogenic organisms is a primary function, disinfectants are also used as oxidants in drinking water treatment for several other functions:

1. Minimization of DBP formation
2. Control of nuisance Asiatic clams and zebra mussels
3. Oxidation of iron and manganese
4. Prevention of regrowth in the distribution system and maintenance of biological stability
5. Removal of taste and odors through chemical oxidation
6. Improvement of coagulation and filtration efficiency
7. Prevention of algal growth in sedimentation basins and filters
8. Removal of color

A brief discussion of these additional oxidant uses follows.

17.10.5.1 Minimization of DBP Formation

Strong oxidants may play a role in disinfection and DBP control strategies in water treatment. Several strong oxidants, including potassium permanganate and ozone, may be used to control DBP precursors.

Note: Potassium permanganate can be used to oxidize organic precursors at the head of the treatment plant, minimizing the formation of by-products at the downstream disinfection stage of the plant. The use of ozone for oxidation of DBP precursors is currently being studied. Early work has shown that the effects of ozonation, prior to chlorination, were highly site-specific and unpredictable. The key variables that seem to determine the effect of ozone are dose, pH, alkalinity, and the nature of the organic material. Ozone has been shown to be effective for DBP precursor reduction at low pHs. At higher pHs (i.e., above 7.5), ozone may actually increase the amount of chlorination by-product precursors.

17.10.5.2 Control of Nuisance Asiatic Clams and Zebra Mussels

The Asiatic clam (*Corbicula fluminea*) was introduced to the U.S from Southeast Asia in 1938 and now inhabits almost every major river system south of 40° latitude.[12]

Asiatic clams have been found in the Trinity River, TX; the Ohio River at Evansville, IN; New River at Narrows and Glen Lyn, VA; and the Catawba River in Rock Hill, SC.[13]

This animal has invaded many water utilities, clogging source water transmission systems and valves, screens, and meters; damaging centrifugal pumps; and causing taste and odor problems.[14]

Cameron et al. investigated the effectiveness of several oxidants to control the Asiatic clam in both the juvenile and adult phases.[15] As expected, the adult clam was found to be much more resistant to oxidants than the juvenile form. In many cases, the traditional method of control, free chlorination, cannot be used because of the formation of excessive amounts of THMs. As shown in Table 17.8,

TABLE 17.8
The Effects of Various Oxidants on Mortality of the Asiatic Clam

Chemical	Residual (mg/L)	Temperature (°C)	pH	Life Stage	LT50 (d)
Free chlorine	0.5	23	8.0	Adult	8.7
	4.8	21	7.9	Adult	5.9
	4.7	16	7.8	Juvenile	4.8
Potassium	1.1	17	7.6	Juvenile	7.9
Permanganate	4.8	17	7.6	Juvenile	8.6
Chlorine dioxide	1.2	24	6.9	Juvenile	0.7
	4.7	22	6.6	Juvenile	0.6

Source: Adapted from Cameron G.N. et al., *J. AWWA*, 81, 53–62, 1989. With permission

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Cameron et al. compared the effectiveness of four oxidants for controlling the juvenile Asiatic clam in terms of the LT50 (time required for 50% mortality).[15] Monochloramine was found to be the best for controlling the juvenile clams without forming THMs. Further research showed that the effectiveness of monochloramine increased greatly as the temperature increased.[16] Note that the temperature in this study reflects conditions in the Lynchburg Reservoir, Houston, TX. Clams can tolerate temperatures between 2 and 35°C.[16]

In a similar study, Belanger et al. studied the biocidal potential of total residual chlorine, monochloramine, monochloramine plus excess ammonia, bromine, and copper for controlling the Asiatic clam.[17] Belanger et al. showed that monochloramine with excess ammonia was the most effective for controlling the clams at 30°C. Chlorination at 0.25 to 0.40 mg/L total residual chlorine at 20 to 25°C controlled clams of all sizes, but had minimal effect at 12 to 15°C (as low as zero mortality).[17] As in other studies, the toxicity of all the biocides was highly dependent on temperature and clam size.

The zebra mussel (*Dreissena polymorpha*) is a recent addition to the fauna of the Great Lakes. It was first found in Lake St. Clair in 1988, though it is believed that this native of the Black Sea and Caspian Sea was brought over from Europe in ballast water around 1985.[18] The zebra mussel population in the Great Lakes has expanded very rapidly, both in size and geographical distribution.[19] Lang reported that zebra mussels have been found in the Ohio River, Cumberland River, Arkansas River, Tennessee River, and the Mississippi River south to New Orleans.[20]

Klerks and Fraleigh evaluated the effectiveness of hypochlorite, permanganate, and hydrogen peroxide with iron for their effectiveness controlling adult zebra mussels.[21] Both continuous and intermittent 28-d static renewal tests were conducted to determine the impact or intermittent dosing. Intermittent treatment proved to be much less effective than continuous dosing.

The hydrogen peroxide-iron combination (1 to 5 mg/L with 25% iron) was less effective in controlling the zebra mussel than either permanganate or hypochlorite. Permanganate (0.5 to 2.5 mg $KnnO_4$/L) was usually less effective than hypochlorite (0.5 to 10 mg Cl_2/L).

Van Benschoten et al. developed a kinetic model to predict the rate of mortality of the zebra mussel in response to chlorine. The model shows the relationship between chlorine residual and temperature on the exposure time required to achieve 50 and 95% mortality. Data were collected for chlorine residuals between 0.5 and 3.0 mg Cl_2/L and temperatures from 0.3 to 24°C. The results show a strong dependence on temperature and required contact times ranging from 2 d to more than a month, depending on environmental factors and mortality required.[22]

Brady et al. compared the efficiency of chlorine to control growth of zebra mussel and quagga mussel (*Dreissenda bugensis*). The quagga mussel is a newly identified mollusk within the Great Lakes that is similar in appearance to the zebra mussel. Full-scale chlorination treatment found a significantly higher mortality for the quagga mussel. The required contact time for 100% mortality for quagga and zebra mussels was 23 d and 37 d, respectively, suggesting that chlorination programs designed to control zebra mussels should also be effective for controlling populations of quagga mussels.[23]

Mastisoff et al. evaluated chlorine dioxide (ClO_2) to control adult zebra mussels using simple, intermittent, and continuous exposures. A single 30-min exposure to 20 mg/L ClO_2 or higher concentration induced at least 50% mortality; sodium hypochlorite produced only 26% mortality, and permanganate and hydrogen peroxide were totally ineffective when dose at 30 mg/L for 30 min under the same conditions. These high dosages, even though only used for a short period, may not allow application directly in water for certain applications due to by-products that remain in the water. Continuous exposure to chlorine dioxide for 4 d was effective at concentrations above 0.5 mg/L (LC50 = 0.35 mg/L), and 100% mortality was achieved at ClO_2 concentrations above 1 mg/L.[24]

These experiences all show that the dose required to induce mortality to these nuisance organism is extremely high, both in terms of chemical dose and contact time. The potential impact on DBPs is significant, especially when the water is high in organic content with a high propensity to form THMs and other DBPs.

17.10.5.3 Oxidation of Iron and Manganese

Iron and manganese occur frequently in groundwaters, but are less problematic in surface waters. Although not harmful to human health at the low concentrations typically found in water, these compounds can cause staining and taste problems. These compounds are readily treated by oxidation to produce a precipitant that is removed in subsequent sedimentation and filtration processes.

Almost all the common oxidants except chloramines will convert ferrous (2+) iron to the ferric (3+) state and manganese (2+) to the (4+) state, which will precipitate as ferric hydroxide and manganese dioxide, respectively.[10] The precise chemical composition of the precipitate will depend on the nature of the water, temperature, and pH.

Table 17.9 shows that oxidant doses for iron and manganese control are relatively low. In addition, the reactions are relatively rapid, occurring on the order or seconds, while DBP formation occurs over hours. With proper dosing, residual chlorine during iron and manganese oxidation is therefore relatively low and short lived. These factors reduce the potential for DBP formation as a result of oxidation for iron and manganese removal.

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TABLE 17.9
Oxidant Doses Required for Oxidation of Iron and Manganese

Oxidant	Iron (II) (mg/mg Fe)	Manganese (II) (mg/mg Mn)
Chlorine	0.62	0.77
Chlorine dioxide	1.21	2.45
Ozone	0.43	0.85
Oxygen	0.14	0.29
Potassium permanganate	0.94	1.92

Source: Adapted from Culp G.L. and Culp, R.L., *New Concepts in Water Purification,* Van Nostrand Reinhold, New York, 1974.

17.10.5.4 Prevention of Regrowth in the Distribution System and Maintenance of Biological Stability

Biodegradable organic compounds and ammonia in treated water can cause microbial growth to the distribution system. Biological stability refers to a condition wherein the water quality does not enhance biological growth in the distribution system. Biological stability can be accomplished in several ways:

1. Removing nutrients from the water prior to distribution
2. Maintaining a disinfectant residual in the treated water
3. Combining nutrient removal and disinfectant residual maintenance

To maintain biological stability in the distribution system, the Total Coliform Rule requires that treated water have a residual disinfectant of 0.2 mg/L when entering the distribution system. A measurable disinfectant residual must be maintained in the distribution system, or the utility must show through monitoring that the heterotrophic plate count remains less than less than 500/100 mL. A system remains in compliance as long as 95% of samples meet these criteria. Chlorine, monochloramine, and chlorine dioxide are typically used to maintain a disinfectant residual in the distribution system. Filtration can also be used to enhance biological stability by reducing the nutrients in the treated water.

The level of secondary disinfectant residual maintained is low, typically in the range of 0.1 to 0.3 mg/L, depending on the distribution system and water quality. Because the contact times in the system are quite long, it is possible to generate significant amounts of DBPs in the distribution system, even at low disinfectant doses.

Distribution system problems associated with the use of combined chlorine residual (chloramines) or no residual have been documented in several instances. The use of combined chlorine is characterized by an initial satisfactory phase in which chloramine residuals are easily maintained throughout the system and bacterial counts are very low. Problems may develop over a period of years, including increased bacterial counts, reduced combined chlorine residual, increased taste and odor complaints, and reduced transmission main carrying capacity. Conversion of the system to free-chlorine residual produces an initial increase in consumer complaints of taste and odors resulting from oxidation of accumulated organic material. Also, it is difficult to maintain a free-chlorine concentration at the ends of the distribution system.[10]

17.10.5.5 Removal of Taste and Odors through Chemical Oxidation

Taste and odors in drinking water are caused by several sources, including microorganisms; decaying vegetation; hydrogen sulfide; and specific compounds of municipal, industrial, or agricultural origin. Disinfectants can also create taste and odor problems. In addition to a specific taste-and odor-causing compound, the sanitary impact is often accentuated by a combination of compounds. More recently, significant attention has been given to tastes and odors from specific compounds such as geosmin, 2-methylisoborneol (MIB), and chlorinated inorganic and organic compounds.[25]

Oxidation is commonly used to remove taste and odor causing compounds. Because many of these compounds are very resistant to oxidation, advanced oxidation processes (ozone/hydrogen peroxide, ozone/UV, etc.) and ozone by itself are often used to address taste and odor problems. The effectiveness of various chemicals to control taste and odors can be site-specific. Suffet et al. found that ozone is generally the most effective oxidant for use in taste and odor treatment. They found that ozone doses of 2.5 to 2.7 mg/L and 10 min of contact time (residual 0.2 mg/L) significantly reduce levels of taste and odors.[26] Lalezary et al. used chlorine, chlorine dioxide, ozone, and permanganate to treat earthy-musty smelling compounds. In that study, chlorine dioxide was found most effective, although none of the oxidants were able to remove geosmin and MIB by more than 40 to 60%. Potassium permanganate has been used in doses of 0.25 to 20 mg/L.[27] Studies at the Metropolitan Water District of Southern California demonstrated the effectiveness of peroxone (ozone plus hydrogen peroxide) to remove geosmin and MIB in water treatment.[28]

Prior experiences with taste and odor treatment indicate that oxidant doses are dependent on the source or the water and causative compounds. In general, small doses can be effective for many taste and odor compounds, but

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some of the difficult-to-treat compounds require strong oxidants such as ozone and advanced oxidation processes or alternative technologies such as granular activated carbon (GAC) adsorption.

17.10.5.6 Improvement of Coagulation and Filtration Efficiency

Oxidants, specifically ozone, have been reported to improve coagulation and filtration efficiency.[29] Others, however, have found no improvement in effluent turbidity from oxidation.[30] Prendiville collected data from a large treatment plant showing that preozonation was more effective than prechlorination to reduce filter effluent turbidities.[31] The cause of and improved coagulation is not clear, but several possibilities have been offered,[32] including:

1. Oxidation of organics into more polar forms
2. Oxidation of metal ions to yield insoluble complexes such as ferric iron complexes
3. Change in the structure and size of suspended particles.

17.10.5.7 Prevention of Algal Growth in Sedimentation Basins and Filters

Prechlorination is often used to minimize operational problems associated with biological growth in water treatment plants.[33] Prechlorination will prevent slime formation on filters, pipes, and tanks. It will also reduce potential taste and odor problems associated with such slimes. Many sedimentation and filtration facilities operate with a small chlorine residual to prevent growth of algae and bacteria in the launders and on the filter surfaces. This practice has increased in recent years as utilities take advantage of additional contact time in the treatment units to meet disinfection requirements under the SWTR.

17.10.5.8 Removal of Color

Free chlorine is used for color removal. A low pH is favored. Humic compounds that have a high potential for DBP formation cause color. The chlorine dosage and kinetics for color removal are best determined through bench studies.

17.10.6 Types of DBPs and Disinfection Residuals

Table 17.10 is a list complied by EPA of DBPs and disinfection residuals that may be of health concern. The table includes both the disinfectant residuals and the specific by-products produced by the disinfectants of interest in drinking water treatment. These contaminants of concern are grouped into four distinct categories and include disinfectant residuals, inorganic by-products, organic oxidation by-products, and halogenated organic by-products.

The production of DBPs depends on the type of disinfectant, the presence of organic material (e.g., total organic carbon [TOC]), bromide ion, and other environmental factors as discussed in this section. By removing DBP precursors, the formation of DBPs can be reduced.

The health effects of DBPs and disinfectants are generally evaluated with epidemiological studies and toxicological studies using laboratory animals. Table 17.11 indicates the cancer classifications of both disinfectants and DBPs as of January 1999. The classification scheme used by USEPA is shown in the bottom of Table 17.11. The USEPA classification scheme for carcinogenicity weighs both animal studies and epidemiologic studies, but places greater weight on evidence of carcinogenicity in humans.

17.10.6.1 Disinfection By-Product Formation

Halogenated organic by-products are formed when natural organic matter (NOM) reacts with free chlorine or free bromine. Free chlorine can be introduced to water directly as a primary or secondary disinfectant, with chlorine dioxide, or with chloramines. Free bromine results from the oxidation of the bromide ion in source water. Factors affecting formation of halogenated DBPs include type and concentration of natural organic matter, oxidant type and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature. Organic nitrogen significantly influences the formation of nitrogen containing DBPs, such as haloacetonitriles, halopicrins, and cyanogen halides.[34] The parameter TOX represents the concentration of total organic halides in a water sample (calculated as chloride). In general, less than 50% of the TOX content has been identified, despite evidence that several of these unknown halogenated by-products of water chlorination may be harmful to humans.[35]

Nonhalogenated DBPs are also formed when strong oxidants react with organic compounds found in water. Ozone and peroxone oxidation of organics lead to the production of aldehydes; aldo- and keto-acids; organic acids; and, when bromide ion is present, brominated organics.[36] Many of the oxidation by-products are biodegradable and appear as biodegradable dissolved organic carbon and assimilable organic carbon in treated water.

Bromide ion plays a key role in DBP formation. Ozone or free chlorine oxidizes bromide ion to hypobromate ion or hypobromous acid, which subsequently forms brominated DBPs. Brominated organic by-products include compounds such as bromoform, brominated acetic acids and acetonitriles, bromopicrin, and cyanogen bromide. Only about one-third of the bromide ions incorporated into by-products has been identified.

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TABLE 17.10
List of Disinfection By-Products and Disinfection Residuals

Disinfectant residuals	Halogenated organic by-products
Free chlorine	Trihalomethanes
Hypochlorous acid	Chloroform
Hypochlorite ion	Bromodichloromethane
Chloramines	Dibromochloromethane
Monochloramine	Bromoform
Chlorine dioxide	Haloacetic acids
Inorganic by-products	Monochloroacetic acid
Chlorate ion	Dichloroacetic acid
Chlorite ion	Trichloroacetic acid
Bromate ion	Monobromoacetic acid
Iodate ion	Dibromoacetic acid
Hydrogen peroxide	Haloacetonitriles
Ammonia	Dichloroacetronitrile
Organic oxidation by-products	Bromochloroacetonitrile
Aldehydes	Dibromoacetonitrile
Formaldehyde	Trichloroacetonitrile
Acetaldehyde	Haloketones
Glyoxal	1,1-Dichloropropanone
Hexanal	1,1,1-Trichloropropanone
Heptanal	Chlorophenols
Carboxylic acids	2-Chlorophenol
Hexanoic acid	2,4-Dichlorophenol
Heptanoic acid	2,4,6-Trichlorophenol
Oxalic acid	Chloropicrin
Assimilable organic carbon	Chloral hydrate
	Cyanogen chloride
	N-Organochloramines

Source: U.S. Environmental Protection Agency, Drinking Water Regulations and Health Advisories, EPA 822-B-96-002, October 1996.

17.10.6.1.1 Disinfection By-Product Precursors

Numerous researchers have documented that NOM is the principal precursor of organic DBP formation.[37] Chlorine reacts with NOM to produce a variety of DBPs, including THMs, haloacetic acids (HAAs), and others. Ozone reacts with NOM to produce aldehydes, organic acids, and aldo- and keto-acids; many of these are produced by chlorine as well.[38]

Natural waters contain mixtures of both humic and nonhumic organic substances. NOM can be subdivided into a hydrophobic fraction composed of primarily humic material, and a hydrophilic fraction composed of primarily fulvic material.

The type and concentration of NOM are often assessed using surrogate measures. Although surrogate parameters have limitations, they are used because they may be measured more easily, rapidly, and inexpensively than the parameter of interest, often allowing on-line monitoring of the operation and performance of water treatment plants. Surrogates used to assess NOM include:

1. TOC and dissolved organic carbon (DOC).
2. Specific UV absorbance (SUVA) — The absorbance at 254 nm wavelength (UV-254) divided by DOC (SUVA = (UV-254/DOC)100 in L/mg-m).
3. THM formation potential — A test measuring the quantity of THMs formed with a high dosage of free chlorine and a long reaction time.
4. TTHM Stimulated Distribution System — A test to predict the TTHM concentration at some selected point in a given distribution system, where the conditions of the chlorination test simulate the distribution system at the point desired.

On average, about 90% of the TOC is dissolved. DOC is defined as the TOC able to pass through a 0.45 μm filter. UV absorbance is a good technique for assessing the presence of DOC through a 0.45 μm filter. This is because DOC primarily consists of humic substances that contain aromatic structures that absorb light in the UV spectrum.

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TABLE 17.11
Status of Health Information for Disinfectants and DBPs

Contaminant	Cancer Classification
Chloroform	Probable human carcinogen
Bromodichloromethane	Probable human carcinogen
Dibromochloromethane	Possible human carcinogen
Bromoform	Probable human carcinogen
Monochloroacetic acid	Not classifiable
Dichloroacetic acid	Probable human carcinogen
Trichloroacetic acid	Possible human carcinogen
Dichloroacetonitrile	Possible human carcinogen
Bromochloroacetonitrile	Not classifiable
Dibromoacetonitrile	Possible human carcinogen
Trichloroacetonitrile	Not classifiable
1,1-Dichloropropanone	Not classifiable
1,1,1-Trichloropropanone	Not classifiable
2-Chlorophenol	Not classifiable
2,4-Dichlorphenol	Not classifiable
2,4,6-Trichlorophenol	Probable human carcinogen
Chloropicrin	Not classifiable
Chloral hydrate	Possible human carcinogen
Cyanogen chloride	Not classifiable
Formaldehyde	Probable human carcinogen
Chlorate	Not classifiable
Chlorite	Not classifiable
Bromate	Probable human carcinogen
Ammonia	Not classifiable
Hypochlorous acid	Not classifiable
Hypochlorite	Not classifiable
Monochloramine	Not classifiable
Chlorine dioxide	Not classifiable

Source: U.S. Environmental Protection Agency, *Drinking Water Regulations and Health Advisories*, EPA 822-B-96–002, October 1996.

Oxidation of DOC reduces the UV absorbance of the water because of the oxidation of some of the organic bonds that absorb UV absorbance. Complete mineralization of organic compounds to carbon dioxide usually does not occur under water treatment conditions; therefore, the overall TOC concentration usually is constant.

DBP concentrations vary seasonally and are typically greatest in the summer and early fall for several reasons:

1. The rate of DBP formation increases with increasing temperature.[36]
2. The nature of organic DBP precursors varies with season.[36]
3. Due to warmer temperatures, chlorine demand may be greater during summer months, requiring higher dosages to maintain disinfection.

If the bromide ion is present in source waters, it can be oxidized to hypobromous acid that can react with NOM to form brominated DBPs such as bromoform. Furthermore, under certain conditions, ozone may react with the hypobromite ion to form bromate ion.

The ratio of bromide ion to the chlorine dose affects THM formation and bromine substitution of chlorine. Increasing the bromide ion to chlorine dose ratio shifts the speciation of THMs to produce more brominated forms.[39] In the Krasener et al. study, the chlorine dose was roughly proportional to TOC concentration. As TOC was removed through the treatment train, the chlorine dose decreased and TTHM formation declined. At the same time, the bromide ion to chlorine dose increased, shifting TTHM concentrations to the more brominated THMs. Improving the removal of NOM prior to chlorination can shift the speciation of halogenated by-products toward more brominated forms.

Chloropicrin is produced by the chlorination of humic materials in the presence of nitrate ion.[40] Thibaud et al. chlorinated humic compounds in the presence of bromide ion to demonstrate the formation of brominated analogs to chloropicrin.[41]

17.10.6.1.2 Impacts of pH on DBP Formation

The pH of water being chlorinated has an impact on the formation of halogenated by-products as shown in Table 17.12.[42] THM formation increases with increasing pH. Trichloroacetic acid, dichloroacetonitile, and trichloropropanone formation decrease with increased pH. Overall TOX formation decreases with increasing pH.

Based on chlorination studies of humic material in model systems, high pH tends to favor chloroform formation over the formation of trichloroacetic acid and other organic halides. Accordingly, water treatment plants practicing precipitative softening at pH values greater than 9.5 to 10 are likely to have a higher fraction of TOX attributable to THMs than plants treating surface waters by conventional treatment in pH ranges of 6 to 8.[35]

Since the application of chlorine dioxide and chloramines may introduce free chlorine into water, chlorination by-products that may be formed would be influenced by pH as discussed above. Ozone application to bromide ion containing waters at high pH favors the formation of bromate ion, while application at low pH favors the formation of brominated organic by-products.

The pH also impacts enhanced coagulation (i.e., for IESWTR compliance) and Lead and Copper Rule compliance. These issues are addressed in EPA's *Microbial and Disinfection By-product Simultaneous Compliance Guidance Manual.*

17.10.6.1.3 Organic Oxidation By-Products

Organic oxidation by-products are formed by reactions between NOM and all oxidizing agents added during

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TABLE 17.12
Conditions of Formation of DBPs

By-Product	Conditions of Formation: Chlorination at pH 5.0	Conditions of Formation: Chlorination at pH 7.0
Total trihalomethanes	Lower formation	
Trichloroacetic acid	Similar formation to that at pH 7.0	Similar formation to that at pH 5.0
Dichloroacetic acid	Similar formation to that at pH 5.0 and 9.4; perhaps slightly highly at pH 7.0	Similar formation to that at pH 5.0 and 9.4; perhaps slightly higher at pH 7.0
Monochloroacetic acid	At concentrations <5 μg/L, trends not discernible	At concentrations <5 μg/L, trends not discernible
Dibromoacetic acid	At concentrations <1 μg/L, trends not discernible	At concentrations <1 μg/L, trends not discernible
Chloral hydrate	Similar formation to that at pH 7.0	Similar formation to that at pH 5.0
Chloropicrin	At concentrations <1 μg/L, trends not discernible	At concentrations <1 μg/L, trends not discernible
Dichloroacetonitrile	Higher formation	Forms within 4 h; decays over time to <5 μg/L
Bromochloroacetonitrile	At concentrations <2 μg/L, trends not discernible	At concentrations <2 μg/L, trends not discernible
Dibromoacetonitrile	At concentrations <5 μg/L, trends not discernible	At concentrations <5 μg/L, trends not discernible
Trichloroacetonitrile	Not detected	Not detected
1,1,1-Trichloropropanone	Higher formation	At concentrations <2 μg/L, trends not discernible

Source: Adapted from Stevens, A.A., Moore, L.A., and Miltner, R.J., *J. AWWA*, 81, 54–60, 1989.

TABLE 17.13
Inorganic DBPs Produced During Disinfection

Disinfectant	Inorganic By-Product or Disinfectant Residual Discussed
Chlorine dioxide	Chlorine Dioxide; chlorite ion; chlorate ion; bromate ion
Ozone	Bromate ion; hydrogen peroxide
Chloramination	Monochloramine; dichloramine; trichloramine; ammonia

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

drinking water treatment. Some of these by-products are halogenated, as discussed in the previous section, while others are not. The types and concentrations of organic oxidation by-products produced depend on the type and dosage of the oxidant being used, chemical characteristics and concentration of the NOM being oxidized, and other factors such as the pH and temperature.

17.10.6.1.4 Inorganic By-Products and Disinfectants

Table 17.13 shows some of the inorganic DBPs that are produced or remain as residual during disinfection. As discussed earlier, bromide ion reacts with strong oxidants to form bromate ion and other organic DBPs. Chlorine dioxide and chloramines leave residuals that are of concern for health considerations, as well as for taste and odor.

17.10.6.2 DBP Control Strategies

In 1983, EPA identified technologies, treatment techniques, and plant modifications that community water systems could use to comply with the maximum contaminant level for TTHMs. The principal treatment modifications involved moving the point of chlorination downstream in the water treatment plant, improving the coagulation process to enhance the removal of DBP precursors, and using chloramines to supplement or replace the use of free chlorine.[38] Moving the point of chlorination downstream in the treatment train often is very effective in reducing DBP formation; it allows the NOM precursor concentration to be reduced during treatment prior to chlorine addition. Replacing prechlorination by preoxidation with an alternate disinfectant that produces less DBPs is another option for reducing formation of chlorinated by-products.

Other options to control the formation of DBPs include source water quality control, DBP precursor removal, and disinfection strategy selection. An overview of each is provided below.

17.10.6.2.1 Source Water Quality Control

Source water control strategies involve managing the source water to lower the concentrations of NOM and bromide ion in the source water. Research has shown that algal growth leads to the production of DBP precursors.[43] Therefore, nutrient and algal management is one method of controlling DBP formation potential of source waters. Control of bromide ion in source waters may be accomplished by preventing brine or salt water intrusion into the water source.

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17.10.6.2.2 DBP Precursor Removal

Raw water can include DBP precursors in both dissolved and particulate forms. For the dissolved precursors to be removed in conventional treatment, they must be converted to particulate form for subsequent removal during settling and filtering. The THM formation potential generally decreases by about 50% through conventional coagulation and settling, indicating the importance of moving the point of chlorine application after coagulation and settling (and even filtration) to control TOX as well as TTHM formation.[44] Conventional systems can lower the DBP formation potential of water prior to disinfection by further removing precursors with enhanced coagulation, GAC adsorption, or membrane filtration prior to disinfection. Precursor removal efficiencies are site-specific and vary with different source waters and treatment techniques.

Aluminum (alum) and iron (ferric) salts can remove variable amounts of NOM. For alum, the optimal pH for NOM removal is in the range of 5.5 to 6.0. The addition of alum decreases pH and may allow the optimal pH range to be reached without acid addition. Waters with very low or very high alkalinities may require the addition of a base or an acid to reach the optimal NOM coagulation pH.[36]

GAC adsorption can be used following filtration to remove additional NOM. For most applications, empty bed contact times in excess of 20 min are required, with regeneration frequencies on the order of 2 to 3 months.[36] These long control times and frequent regeneration requirements make GAC an expensive treatment option. In cases where prechlorination is practiced, the chlorine rapidly degrades GAC. Addition of a disinfectant to the GAC bed can result in specific reactions in which previously absorbed compounds leach into the treated water.

Membrane filtration has been shown effective in removing DBP precursors in some instances. In pilot studies, ultrafiltration (UF) with a molecular weight cutoff (MWCO) of 100,000 Da was ineffective for controlling DBP formation. However, when little or no bromide ion was present in source water, nanofiltration (NF) membranes with MWCOs of 400 to 800 Da effectively controlled DBP formation.[45]

In waters containing bromide ion, higher bromoform concentrations were observed after chlorination of membrane permeate (compared with raw water). This occurs as a result of filtration removing NOM while concentrating bromide ions in the permeate thus providing a higher ratio of bromide ions to NOM than in raw water. This reduction in chlorine demand increases the ratio of bromide to chlorine, resulting in higher bromoform concentrations after chlorination of NF membrane permeate (compared with the raw water). TTHMS were lower in chlorinated permeate than chlorinated raw water. Due to the shift in speciation of THMs toward more brominated forms, bromoform concentrations were actually greater in chlorinated treated water than in chlorinated raw water. The use of spiral-wound NF membranes (200 to 300 Da) more effectively controlled the formation of brominated THMs, but pretreatment of the water was necessary.[45] Significant limitations in the use of membranes are the disposal of the waste brine generated, fouling of membranes, cost of membrane replacement, and increased energy cost.

TABLE 17.14
Required Removal of TOC by Enhanced Coagulation for Surface Water Systems Using Convention Treatment (percent reduction)

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0–60	>60–120	>120
>2.0–4.0	35.0	25.0	15.0
>4.0–8.0	45.0	35.0	25.0
>8.0	50.0	40.0	30.0

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

The promulgated disinfection by-product regulations (DBPR) require enhanced coagulation as an initial step for removal of DBP precursors. In addition to meeting MCLs and maximum residual disinfection levels (MRDLs), some water suppliers also must meet treatment requirements to control the organic material (DBP precursors) in the raw water that combines with disinfectant residuals to form DBPs. Systems using conventional treatment are required to control precursors (measured as TOC) by using enhanced coagulation or enhanced softening. A system must remove a specified percentage of TOC (based on raw water quality) prior to the point of continuous disinfection (Table 17.14).

Systems using ozone followed by biologically active filtration or chlorine dioxide that meet specific criteria would be required to meet the TOC removal requirements prior to addition of a residual disinfectant. Systems able to reduce TOC by a specified percentage level have met the DBPR treatment technique requirements.

If the system does not meet the percent reduction, it must determine its alternative minimum TOC removal level. The primacy agency approves the alternative minimum TOC removal possible for the system on the basis of the relationship between coagulant dose and TOC in the system based on results of bench or pilot-scale testing. Enhanced coagulation is determined in part as the coagulant dose where an incremental addition of 10 mg/L of alum (or an equivalent amount of ferric salt) results in a TOC removal below 0.3 mg/L.

17.10.6.2.3 Disinfection Strategy Selection

In addition to improving the raw or predisinfectant water quality, alternative disinfection strategies can be used to control DBPs. These strategies include the following:

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TABLE 17.15
CT Values for Inactivation of Viruses

Disinfectant (@ 10°C)	Units	Inactivation 2-log	Inactivation 3-log
Chlorine	mg · min/L	4	4
Chloramine	mg · min/L	643	1067
Chlorine dioxide	mg · min/L	4.2	12.8
Ozone	mg · min/L	0.5	0.8
UV	mW · sec/cm^2	21	36

Source: Modified from data obtained from American Water Works Association, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Works Systems using Surface Water Sources*, 1991.

1. Use an alternative or supplemental disinfectant or oxidant such as chloramines or chlorine dioxide that will produce fewer DBPs.
2. Move the point of chlorination to reduce TTHM formation and, where necessary, substitute chloramines, chlorine dioxide, or potassium permanganate for chlorine as a preoxidant.
3. Use two different disinfectants or oxidants at various points in the treatment plant to avoid DBP formation at locations where precursors are still present in high quantities.
4. Use of powdered activated carbon for THM precursor or TTHM reduction seasonally or intermittently.
5. Maximize precursor removal.

17.10.6.3 CT Factor

One of the most important factors for determining or predicting the germicidal efficiency of any disinfectant is the CT factor, a version of the Chick-Watson law.[46] The CT factor is defined as the product of the residual disinfectant concentration, C (in milligrams per liter), and the contact time, (T) (in minutes), that residual disinfectant is in contact with the water.

EPA developed CT values for the inactivation of giardia and viruses under the SWTR. Table 17.15 compares the CT values for virus inactivation using chlorine, chlorine dioxide, ozone, chloramine, and UV light disinfection under specified conditions. Table 17.16 shows the CT values for inactivation of giardia cyst using chlorine, chloramine, chlorine dioxide, and ozone under specified conditions. The CT values shown in Table 17.15 and Table 17.16 are based on water temperatures of 10°C and pH values in the range of 6 to 9. CT values for chlorine disinfection are based on a free chlorine residual. Note that chlorine is less effective as pH increases from 6 to 9. In addition, for a given CT value, a low C and a high T is more effective than a high C and a low T. For all disinfectants, as temperature increases, effectiveness increases.

TABLE 17.16
CT Values for Inactivation of Giardia Cysts

Disinfectant (@ 10°C)	Inactivation (mg · min/L) 1-log	Inactivation (mg · min/L) 2-log	Inactivation (mg · min/L) 3-log
Chlorine	35	69	104
Chloramine	615	1240	1850
Chorine dioxide	7.7	15	23
Ozone	0.48	0.95	1.43

Source: Modified from data obtained from American Water Works Association, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Works Systems using Surface Water Sources*, 1991.

17.10.7 Pathogen Inactivation vs. DBP Formation

Table 17.17 presents a summary of disinfection parameter impacts on pathogen inactivation and DBP formation.

17.10.8 Disinfectant Residual Regulatory Requirements

One of the most important factors for evaluating the merits of alternative disinfectants is their ability to maintain the microbial quality in the water distribution system. Disinfectant residuals may serve to protect the distribution system against regrowth.[47] The SWTR requires that filtration and disinfection must be provided to ensure that the total treatment of the system achieves at least a 3-log removal or inactivation of giardia cysts and a 4-log removal or inactivation of viruses. In addition, the disinfection process must demonstrate by continuous monitoring and recording that the disinfection residual in the water entering the distribution system is never less than 0.2 mg/L for more than 4 h.

Several of the alternative disinfectants examined in this handbook cannot be used to meet the residual requirements stated in the SWTR. For example, if either ozone or UV light disinfection is used as the primary disinfectant, a secondary disinfectant, such as chlorine or chloramines, should be utilized to obtain a residual in the distribution system.

DBP formation continues in the distribution system due to reactions between the residual disinfectant and organics in the water. Koch et al. found that with a chlorine dose of 3 to 4mg/L-THM and HAA concentrations increase rapidly during the first 24 h in the distribution system. After the initial 48 h, the subsequent increase in THMs is very small. Chloral hydrate concentrations continued to increase after the initial 24 h, but at a reduced rate. Haloketones actually decreased in the distribution system.[48]

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TABLE 17.17
Summary of Disinfection Impacts

Disinfection Parameter	Typical Impact on Pathogen Inactivation	Typical Impact on DBP Formation
Disinfectant type	Depends on inactivation efficacy	Depends on disinfectant reactivity
Disinfectant strength	The stronger the disinfectant, the quicker the disinfection process	The stronger the disinfectant, the greater the amount of DBPs
Disinfectant dose	Increasing the disinfectant dose increases the disinfection rate	Increasing the disinfectant dose typically increases the rate of DBP formation
Type of organism	Susceptibility to disinfection varies; according to pathogen group; in general, protozoa are more resistant to disinfectants than bacteria and viruses	None
Contact time	Increasing the contact time decreases the disinfectant dose required for a given level of inactivation	Increasing contact time with an equivalent disinfectant dose increases the formation of DBPs
pH	pH may affect the disinfectant form and the efficiency of the disinfectant	The impact of pH varies with DBP
Temperature	Increasing the temperature increases the rate of disinfection	Increasing temperature is typically associated with faster oxidation kinetics and increased DBP formation
Turbidity	Particles responsible for turbidity can surround and shield pathogenic microorganisms from disinfectants	Increased turbidity may be associated with increased NOM, which represents an increased amount of DBP precursors for the formation of DBPs when disinfectant is applied
Dissolved organics	Dissolved organics can interfere with disinfection by creating a demand and reducing the amount of disinfectant available for pathogen inactivation	Increased dissolved organics will represent a larger amount of DBP precursor for the formation of DBPs when disinfectant is applied.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

Nieminski et al. evaluated DBP formation in the simulated distribution systems of treatment plants in Utah. Finished water chlorine residuals ranged from 0.4 to 2.8 mg/L. Generally, THM values in the distribution system studies increased by 50 to 100% (range of 30 to 200%) of the plant effluent value after 24-h contact time. The 24-hour THM concentration was essentially the same as the 7-d THM formation potential. HAA concentrations in the simulated distribution system were about 100% (range of 30 to 200%) of the HAA in the plant effluent. The 7-d HAA formation potential was sometimes higher, or below the distribution system values. If chlorine is used as a secondary disinfectant, one should therefore anticipate a 100-percent increase in the plant effluent THMs or plan to reach the 7-day THM formation level in the distribution system.[49]

17.10.9 Summary of Current National Disinfection Practices

Most water treatment plants disinfect water prior to distribution. The 1995 Community Water Systems Survey reports that 81% of all community water systems provide some form of treatment on all or a portion of their water sources. The survey also found that virtually all surface water systems provide some treatment of their water. Of those systems reporting no treatment, 80% rely on groundwater as their only water source.[2]

The most commonly used disinfectants and oxidants are chlorine, chlorine dioxide, chloramines, ozone, and potassium permanganate. Table 17.18 shows a breakdown on the chemical usage from the survey. Note that the table shows the percentages of systems using the particular chemical as either disinfectant or some other role. The table shows the predominance of chlorine in surface and groundwater disinfection treatment systems with more than 60% of the treatment systems using chlorine as a disinfectant and oxidant. Potassium permanganate, on the other hand, is used by many systems, but its application is primarily for oxidation rather than disinfection.

Permanganate will have some beneficial impact on disinfection since it is a strong oxidant that will reduce the chemical demand for the ultimate disinfection chemical. Chloramine is used by some systems and is more frequently used as a posttreatment disinfectant.

The International Ozone Association conducted a survey of ozone facilities in the U.S.[50] The survey documented the types of ozone facilities, size, objective of ozone application, and year of operation. The most common use of ozone is for oxidation of iron and manganese and taste and odor control. Twenty-four of the 158 ozone facilities used GAC following ozonation. In addition to the 158 operating ozone facilities, the survey identified 19 facilities under construction and another 30 under design. The capacity of the systems range from less than 25 gal/min to exceeding 500 mg. Nearly half of the operating facilities

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TABLE 17.18
Disinfection Practices of Water Systems that include Some Form of Treatment

	Service Population								
Treatment	<100	101–500	501–1000	1001–3300	3301–10,000	10,001–50,000	50,000–100,000	Over 100,001	Total
Surface Water Systems									
Total Number of Systems	218	432	330	845	679	626	103	104	3,337
Predisinfection, Oxidation/Softening									
Chlorine	59.0%	73.9%	67.3%	66.3%	68.8%	58.6%	47.5%	57.1%	63.8%
Chlorine dioxide	0%	0%	0%	5.0%	4.7%	13.2%	14.2%	7.8%	6.3%
Chloramines	4.6%	0%	1.1%	2.1%	0%	2.2%	15.5%	10.8%	3.1%
Ozone	0%	0%	0%	0%	0.3%	0%	5.4%	5.8%	0.9%
$KmnO_4$	0%	4.9%	9.6%	9.9%	15.2%	28.3%	25.9%	28.5%	16.0%
Predisinfection/ oxidation	0%	0%	2.0%	2.9%	0.6%	9.2%	5.1%	4.3%	3.5%
Lime/soda ash softening	6.8%	0%	20.9%	16.2%	14.3%	11.7%	3.5%	5.9%	12.5%
Recarbination	0%	0%	0%	0%	2.1%	4.7%	0.6%	6.3%	1.9%
Postdisinfection									
Chlorine	4.97%	51.6%	80.6%	62.8%	77.9%	71.1%	73.8%	63.6%	67.5%
Chlorine dioxide	0%	0%	0%	0%	0.3%	4.9%	5.9%	11.2%	1.6%
Chloramines	0%	0%	0%	2.9%	2.1%	15.6%	29.4%	24.2%	8.1%
Postdisinfection/ combinations	0%	0%	0%	2.1%	4.0%	3.9%	1.9%	1.6%	3.0%
Groundwater Systems									
Total Number of Systems	9042	10,367	4443	4442	2035	1094	120	56	31,579
Predisinfection, Oxidation/Softening									
Chlorine	64.2%	69.9%	56.7%	73.2%	60.6%	57.4%	36.2%	38.1%	63.9%
Chlorine dioxide	1.3%	0%	0%	0%	0%	0%	3.1%	0%	0.3%
Chloramines	0%	0%	0%	0%	0%	0.6%	1.4%	0.7%	0.1%
Ozone	0%	0%	0%	0%	0%	0%	0%	0.6%	0%
$KmnO_4$	0%	0.9%	2.2%	0.6%	5.8%	3.2%	7.0%	0%	1.8%
Predisinfection/ oxidation	0.3%	0.5%	0%	0.7%	1.0%	2.6%	0%	0%	0.7%
Lime/soda ash softening	2.9%	2.9%	2.2%	3.6%	3.5%	3.8%	5.0%	9.1%	3.2%
Recarbination	0%	0.5%	0%	0.6%	1.4%	1.5%	2.8%	1.1%	0.6%
Postdisinfection									
Chlorine	23.0%	23.4%	32.5%	28.3%	42.5%	41.9%	54.5%	65.8%	31.0%
Chlorine dioxide	0%	1.0%	0%	0%	0%	0.6%	0%	0%	0.4%
Chloramines	0%	0%	0%	0%	0.1%	1.1%	3.9%	4.3%	0.3%
Postdisinfection/ combinations	0%	0%	0%	0%	0.1%	0.1%	0%	0%	0%

Source: U.S. Environmental Protection Agency, *Community Water System Survey*, Vols. I and II; Overview, EPA 815-R-97-001a, 97-001b. January 1997.

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have a capacity exceeding 1 mg. Rice et al. found that as of May 1998, 264 drinking water plants in the U.S. are using ozone.[51]

17.10.10 Summary of Methods of Disinfection

The methods of disinfection are as follows:

1. Heat — Possibly the first method of disinfection. Disinfection is accomplished by boiling water for 5 to 10 minutes. This is good only for household quantities of water when bacteriological quality is questionable.
2. UV light — While a practical method of treating large quantities, adsorption of UV light is very rapid, so the use of this method is limited to nonturbid waters close to the light source.
3. Metal ions — This includes silver, copper, mercury.
4. Alkalis and acids.
5. pH adjustment — The adjustment is a pH under 3.0 or over 11.0.
6. Oxidizing agents — This includes bromine, ozone, potassium permanganate, and chlorine.

The vast majority of drinking water systems in the U.S. use chlorine for disinfection.[52] Along with meeting the desired characteristics listed above, chlorine has the added advantage of a long history of use — it is fairly well understood. Although some small water systems may use other disinfectants, we focus on chlorine in this handbook and provide only a brief overview of other disinfection alternatives.

Note: One of the recent developments in chlorine disinfection is the use of multiple and interactive disinfectants. In these applications, chlorine is combined with a second disinfectant to achieve improved disinfection efficiency and effective DBP control.

Note: As described earlier, the 1995 Community Water System Survey indicated that all surface water and groundwater systems in the U.S. use chlorine for disinfection.[2]

17.10.11 Chlorination

The addition of chlorine or chlorine compounds to water is called chlorination. Chlorination is considered to be the single most important process for preventing the spread of waterborne disease. Chlorine has many attractive features that contribute to its wide use in industry. Five of the key attributes of chlorine are:

1. It causes damage to the cell wall.
2. It alters the permeability of the cell (the ability to pass water in and out through the cell wall).
3. It alters the cell protoplasm.
4. It inhibits the enzyme activity of the cell so it is unable to use its food to produce energy.
5. It inhibits cell reproduction.

There are, however, some concerns regarding chlorine usage that may inspect its uses such as:

1. Chlorine reacts with many naturally occurring organic and inorganic compounds in water to produce undesirable DBPs.
2. Hazards associated with using chlorine, specifically chlorine gas, require special treatment and response programs.
3. High chlorine doses can cause taste and odor problems.

Chlorine is used in water treatment facilities primarily for disinfection. Because of chlorine's oxidizing powers, it has been found to serve other useful purposes in water treatment, inlcuding:[53]

1. Taste and odor control
2. Prevention of algal growths
3. Maintenance of clear filter media
4. Removal of iron and manganese
5. Destruction of hydrogen sulfide
6. Bleaching of certain organic colors
7. Maintenance of distribution system water quality by controlling slime growth
8. Restoration and preservation of pipeline capacity
9. Restoration of well capacity, water main sterilization
10. Improved coagulation

Chlorine is available in a number of different forms: (1) as pure elemental gaseous chlorine (a greenish-yellow gas possessing a pungent and irritating odor that is heavier than air, nonflammable, and nonexplosive) that when released to the atmosphere is toxic and corrosive, (2) as solid calcium hypochlorite (in tablets or granules), or (3) as a liquid sodium hypochlorite solution (in various strengths).

The selection of one form of chlorine over the others for a given water system depends on the amount of water to be treated, configuration of the water system, the local availability of the chemicals, and the skill of the operator.

One of the major advantages of using chlorine is the effective residual that it produces. A residual indicates that disinfection is completed, and the system has an accept-

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able bacteriological quality. Maintaining a residual in the distribution system provides another line of defense against pathogenic organisms that could enter the distribution system and helps to prevent regrowth of those microorganisms that were injured but not killed during the initial disinfection stage.

17.10.11.1 Chlorine Terms

New waterworks operators often have difficulties understanding the terms used to describe the various reactions and processes used in chlorination. Common chlorination terms include the following:

1. Chlorine reaction — Regardless of the form of chlorine used for disinfection, the reaction in water is basically the same. The same amount of disinfection can be expected, provided the same amount of available chlorine is added to the water. The standard term for the concentration of chlorine in water is milligrams per liter or parts per million; these terms indicate the same quantity.
2. Chlorine dose — This is the amount of chlorine added to the system. It can be determined by adding the desired residual for the finished water to the chlorine demand of the untreated water. Dosage can be either milligrams per liter or pounds per day. The most common is milligrams per liter.
3. Chlorine demand — the amount of chlorine used by iron, manganese, turbidity, algae, and microorganisms in the water. Because the reaction between chlorine and microorganisms is not instantaneous, demand is relative to time. For instance, the demand 5 min after applying chlorine will be less than the demand after 20 min. Demand, like dosage, is expressed in milligrams per liter. The chlorine demand is as follows:

$$Cl_2 \text{ Demand} = Cl_2 \text{ Dose} - Cl_2 \text{ Residual} \quad (17.7)$$

4. Chlorine residual — This is the amount of chlorine (determined by testing) that remains after the demand is satisfied. Residual, like demand, is based on time. The longer the time after dosage, the lower the residual will be, until all of the demand has been satisfied. Residual, like dosage and demand, is expressed in milligrams per liter. The presence of a free residual of at least 0.2 to 0.4 ppm usually provides a high degree of assurance that the disinfection of the water is complete. Combined residual is the result of combining free chlorine with nitrogen compounds. Combined residuals are also called chloramines. Total chlorine residual is the mathematical combination of free and combined residuals. Total residual can be determined directly with standard chlorine residual test kits.
5. Chorine contact time — This is one of the key items in predicting the effectiveness of chlorine on microorganisms. It is the interval (usually only a few minutes) between the time when chlorine is added to the water and the time the water passes by the sampling point, contact time is the "T" in CT. CT is calculated based on the free chlorine residual prior to the first customer multiplied by the contact time in minutes.

$$\begin{aligned} CT &= \text{Concentration} \times \text{Contact Time} \\ &= \text{mg/L} \times \text{min} \end{aligned} \quad (17.8)$$

A certain minimum time period is required for the disinfecting action to be completed. The contact time is usually a fixed condition determined by the rate of flow of the water and the distance from the chlorination point to the first consumer connection. Ideally, the contact time should not be less than 30 min, but even more time is needed at lower chlorine doses, in cold weather, or under other conditions.

Pilot studies have shown that specific CT values are necessary for the inactivation of viruses and giardia. The required CT value will vary depending on pH, temperature, and the organisms to be killed. Charts and formulae are available to make this determination.

EPA has set a CT value of 3-log (CT99.9) inactivation to assure the water is free of giardia. State drinking water regulations include charts giving this value for different pH and temperature combinations. Filtration, in combination with disinfection, must provide a 3-log removal or inactivation of giardia. Charts in the EPA's SWTR guidance manual list the required CT values for various filter systems. Under the 1996 IESWTR, EPA requires systems that filter to remove 99% (2 log) of *cryptosporidium* oocysts. To be assured that the water is free of viruses, a combination of filtration and disinfection to provide a 4 log removal of viruses has been judged the best for drinking water safety — 99.99% removal. Viruses are inactivated (killed) more easily than cysts or oocysts.

17.10.11.2 Chlorine Chemistry

The reactions of chlorine with water and the impurities that might be in the water are quite complex, but a basic understanding of these reactions can aid the operator in

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keeping the disinfection process operating at its highest efficiency.

When dissolved in pure water, chlorine reacts with the H^+ ions and the OH^- radicals in the water. Two of the products of this reaction (the actual disinfecting agents) are hypochlorous acid (HOCl) and the hypochlorite radical, (OCl^-). If microorganisms are present in the water, the HOCl and the OCl^- penetrate the microbe cells and react with certain enzymes. This reaction disrupts the organisms' metabolism and kills them.

The chemical equation for hypochlorous acid is as follows:

$$\underset{\text{(chlorine)}}{Cl_2} + \underset{\text{(water)}}{H_2O} \leftrightarrow \underset{\text{(hypochlorous acid)}}{HOCl} + \underset{\text{(hydrochloric acid)}}{HCl} \qquad (17.9)$$

Note: The symbol ↔ indicates that the reactions are reversible.

HOCl is a weak acid; it dissociates slightly into hydrogen and hypochlorite ions, but into a strong oxidizing and germicidal agent. Hydrochloric acid (HCl) in the above equation is a strong acid and retains more of the properties of chlorine. HCl tends to lower the pH of the water, especially in swimming pools where the water is recirculated and continually chlorinated. The total HOCl and hypochlorite ions in water constitute the free available chlorine.

Hypochlorites act in a manner similar to HCl when added to water, because hypochloric acid is formed.

When chlorine is first added to water containing some impurities, the chlorine immediately reacts with the dissolved inorganic or organic substances and is then unavailable for disinfection. The amount of chlorine used in this initial reaction is the chlorine demand of the water. If dissolved ammonia (NH_3) is present in the water, the chlorine will react with it to form compounds called chloramines. Only after the chlorine demand is satisfied and the reaction with all the dissolved ammonia is complete is the chlorine actually available in the form of HOCl and OCl^-. The equation for the reaction of HOCl and NH_3 is as follows:

$$\underset{\text{(hypochlorous acid)}}{HOCl} + \underset{\text{(ammonia)}}{NH_3} \leftrightarrow \underset{\text{(monochloramine)}}{NH_2Cl} + \underset{\text{(water)}}{H_2O} \qquad (17.10)$$

Note: The chlorine as hypochlorous acid and hypochlorite ions remaining in the water after the above reactions are complete is known as free available chlorine, and it is a very active disinfectant.

17.10.11.3 Breakpoint Chlorination

To produce a free chlorine residual, enough chlorine must be added to the water to produce what is referred to as breakpoint chlorination (the point at which near complete oxidation of nitrogen compounds is reached; any residual beyond breakpoint is mostly free chlorine [see Figure 17.9]). When chlorine is added to natural waters, the chlorine begins combining with and oxidizing the chemicals in the water before it begins disinfecting. Although residual chlorine will be detectable in the water, the chlorine will be in the combined form with a weak disinfecting power. As we see in Figure 17.9, adding more chlorine to the water at this point actually decreases the chlorine residual as the additional chlorine destroys the combined chlorine compounds. At this stage, water may have a strong swimming pool or medicinal taste and odor. To avoid this taste and odor, add more chlorine to produce a free residual chlorine. Free chlorine has the highest disinfecting power. The point at which most of the combined chlorine compounds have been destroyed and the free chlorine starts to form is the breakpoint.

The chlorine breakpoint of water can only be determined by experimentation. This simple experiment requires 20 1000-mL breakers and a solution of chlorine. Place the raw water in the beakers and dose with progressively larger amounts of chlorine. For instance, you might start with zero in the first beaker, then 0.5 and 1.0 mg/L, and so on. After a period of time, say 20 min, test each beaker for total chlorine residual and plot the results.

17.10.11.3.1 Breakpoint Chlorination Curve

Refer to Figure 17.9 for the following explanation.

When the curve starts, no residual exists, even though there was a dosage. This is called the initial demand and is microorganisms and interfering agents using the result of the chlorine.

After the initial demand, the curve slopes upward. Chlorine combining to form chloramines produces this part of the curve. All of the residual measured on this part of the curve is combined residual.

At some point, the curve begins to drop back toward zero. This portion of the curve results from a reduction in combined residual. This occurs because enough chlorine has been added to destroy (oxidize) the nitrogen compounds used to form combined residuals.

The breakpoint is the point where the downward slope of the curve breaks upward. At this point, all of the nitrogen compounds that could be destroyed have been destroyed.

After breakpoint, the curve starts upward again, usually at a 45° angle. Only on this part of the curve can free residuals be found.

Notice that the breakpoint is not zero. The distance that the breakpoint is above zero is a measure of the remaining combined residual in the water. This combined residual exists because some of the nitrogen compound will not have been oxidized by chlorine. If irreducible combined residual is more than 15% of the total residual, chlorine odor and taste complaints will be high.

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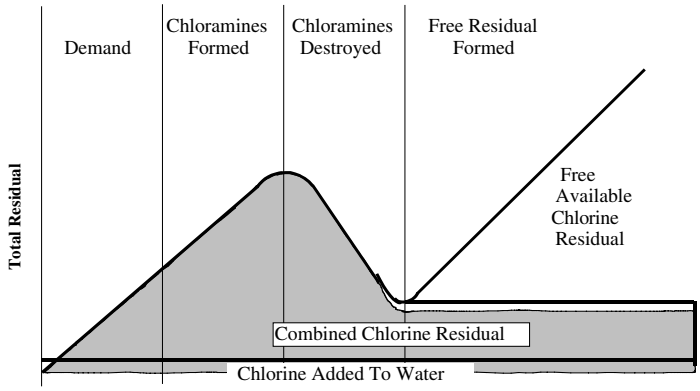

FIGURE 17.9 Breakpoint chlorination curve. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

17.10.11.4 Gas Chlorination

Gas chlorine is provided in 100 lb or 1 ton containers. Chlorine is placed in the container as a liquid. The liquid boils at room temperature, reducing to a gas and building pressure in the cylinder. At room temperature of 70°F, a chlorine cylinder will have a pressure of 85 psi; 100/150-lb cylinders should be maintained in an upright position and chained to the wall. To prevent a chlorine cylinder from rupturing in a fire, the cylinder valves are equipped with special fusible plugs that melt between 158 and 164°F.

Chlorine gas is 99.9% chlorine. A gas chlorinator meters the gas flow and mixes it with water, which is then injected as a water solution of pure chlorine. As the compressed liquid chlorine is withdrawn from the cylinder, it expands as a gas, withdrawing heat from the cylinder. Care must be taken not to withdraw the chlorine at too fast a rate; if the operator attempts to withdraw more than about 40 lb of chlorine/d from a 150-lb cylinder, it will freeze up.

Note: All chlorine gas feed equipment sold today is vacuum operated. This safety feature ensures that if a break occurs in one of the components in the chlorinator, the vacuum will be lost, and the chlorinator will shut down without allowing gas to escape.

Chlorine gas is a highly toxic lung irritant, and special facilities are required for storing and housing it. Chlorine gas will expand to 500 times its original compressed liquid volume at room temperature (1 gal of liquid chlorine will expand to about 67 ft^3). Its advantage as a drinking water disinfectant is the convenience afforded by a relatively large quantity of chlorine available for continuous operation for several days or weeks without the need for mixing chemicals. Where water flow rates are highly variable, the chlorination rate can be synchronized with the flow.

Chlorine gas has a very strong, characteristic odor that can be detected by most people at concentrations as low as 3.5 ppm. Highly corrosive in moist air, it is extremely toxic and irritating in concentrated form. Its toxicity ranges from throat irritating at 15 ppm to rapid death at 1000 ppm. Although chlorine does not burn, it supports combustion, so open flames should never be used around chlorination equipment.

While changing chlorine cylinders, an accidental release of chlorine may occasionally occur. To handle this type of release, an approved (approved by the National Institute for Occupational Safety and Health) self-contained breathing apparatus must be worn. Special emergency repair kits are available from the Chlorine Institute for use by emergency response teams to deal with chlorine leaks. Because chlorine gas is 2.5 times heavier than air, exhaust and inlet air ducts should be installed at floor level. A leak of chlorine gas can be found by using the fumes from a strong ammonia mist solution. A white cloud develops when ammonia mist and chlorine combine.

17.10.11.5 Hypochlorination

Combining chlorine with calcium or sodium produces hypochlorites. Calcium hypochlorites are sold in powder or tablet forms and can contain chlorine concentrations up to 67%. Sodium hypochlorite is a liquid (e.g., bleach) and is found in concentrations up to 16 percent. Chlorine concentrations of household bleach range from 4.75 to 5.25%. Most small system operators find using these liquid or dry chlorine compounds more convenient and safer than chlorine gas.

The compounds are mixed with water and fed into the water with inexpensive solution feed pumps. These pumps are designed to operate against high system pressures, but can also be used to inject chlorine solutions into tanks. Injecting chlorine into the suction side of a pump is not recommended as the chlorine may corrode the pump impeller.

Calcium hypochlorite can be purchased as tablets or granules, with approximately 65% available chlorine (10 lb of calcium hypochlorite granules contain only 6.5 lb of chlorine). Normally, 6.5 pounds of calcium

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hypochlorite will produce a concentration of 50-mg/L chlorine in 10,000 gal of water. Calcium hypochlorite can burn (at 350°F) if combined with oil or grease. When mixing calcium hypochlorite, operators must wear chemical safety goggles, a cartridge breathing apparatus, and rubberized gloves. Always place the powder in the water. Placing the water into the dry powder could cause an explosion.

Sodium hypochlorite is supplied as a clear, greenish-yellow liquid in strengths from 5.25 to 16% available chlorine. Often referred to as bleach, it is used for bleaching. As we stated earlier, common household bleach is a solution of sodium hypochlorite containing 5.25% available chlorine. The amount of sodium hypochlorite needed to produce a 50-mg/L-chlorine concentration in 10,000 gal of water can be calculated using the solutions equation:

$$C_1 \times V_1 = C_2 \times V_2 \qquad (17.11)$$

where
C = the solution concentration (mg/L or %)
V = the solution volume (L, gal, qt, etc.)
1.0% = 10,000 mg/L

In this example, C_1 and V_1 and associated with the sodium hypochlorite and C_2 and V_2 are associated with the 10,000 gal of water with a 50 mg/L chlorine concentration. Therefore:

C_1 = 5.25%
V_1 = unknown volume of sodium hypochlorite
C_2 = 50 mg/L
V_2 = 10,000 gal

$$C_1 = \frac{5.25\% \times 10{,}000 \text{ mg/L} = 52{,}500 \text{ mg/L}}{1.0\%}$$

$$52{,}500 \text{ mg/L} \times V_1 = 50 \text{ mg/L} \times 10{,}000 \text{ gal}$$

$$V_1 = \frac{50 \text{ mg/L} \times 10{,}000 \text{ gal}}{52{,}500 \text{ mg/L}}$$
$$= 9.52 \text{ gal of sodium hypochlorite}$$

Sodium hypochlorite solutions are introduced to the water in the same manner as calcium hypochlorite solutions. The purchased stock bleach is usually diluted with water to produce a feed solution that is pumped into the water system.

Hypochlorites are stored properly to maintain their strengths. Calcium hypochlorite must be stored in airtight containers in cool, dry, dark locations. Sodium hypochlorite degrades relatively quickly even when properly stored; it can lose more than half of its strength in 3 to 6 months. Operators should purchase hypochlorites in small quantities to assure they are used while still strong. Old chemicals should be discarded safely.

A chemical metering pump's pumping rate is usually manually adjusted by varying the length of the piston or diaphragm stroke. Once the stroke is set, the hypochlorinator feeds accurately at that rate. However, chlorine measurements must be made occasionally at the beginning and end of the well pump cycle to assure correct dosage. A metering device may be used to vary the hypochlorinator feed rate, synchronized with the water flow rate. Where a well pump is used, the hypochlorinator is connected electrically with the pump's on-off controls to assure that chlorine solution is not fed into the pipe when the well is not pumping.

17.10.11.6 Determining Chlorine Dosage

Proper disinfection requires calculation of the amount of chlorine that must be added to the water to produce the required dosage. The type of calculation used depends on the form of chlorine being used.

The basic chlorination calculation used is the same one used for all chemical addition calculations — the pounds formula. The pounds formula is

$$\text{Pounds} = \text{mg/L} \times 8.34 \times \text{MG} \qquad (17.12)$$

where
pounds = pounds of available chlorine required
mg/L = desired concentration in milligrams per liter
8.24 = conversion factor
MG = millions of gallons of water to be treated

Example 17.3

Problem:

Calculate the number of pounds of gaseous chlorine needed to treat 250,000 gal of water with 1.2 mg/L of chlorine.

Solution:

$$\text{Pounds} = 1.2 \text{ mg/L} \times 8.34 \times 0.25 \text{ MG}$$
$$= 2.5 \text{ lb}$$

Note: Hypochlorites contain less than 100% available chlorine. We must therefore use more hypochlorite to get the same number of pounds of chlorine into the water.

Using the same problem in Example 17.3, but substituting calcium hypochlorite with 65% available chlorine, 2.5 lb of available chlorine is still needed. However, more than 2.5 lb of calcium hypochlorite is needed to provide that much chlorine. Determine how much of the chemical is needed by dividing the pounds of chlorine needed by the decimal form of the percent available chlorine. Since 65% is the same as 0.65, we need to add the following to get that much chlorine:

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$$\frac{2.5 \text{ lb}}{0.65 \text{ Available Chlorine}} = 3.85 \text{ lb Ca } (OCl^-)$$

In practice, because most hypochlorites are fed as solutions, we often need to know how much chlorine solution we need to feed. In addition, the practical problems faced in day-to-day operation are never so clearly stated as the practice problems we work. For example, small water systems do not usually deal with water flow in million gallons per day. Real-world problems usually require a lot of intermediate calculations to get everything ready to plug into the pounds formula.

EXAMPLE 17.4

Problem:

We have raw water with a chlorine demand 2.2 mg/L. We need a final residual of 1.0 mg/L at the entrance to the distribution system. We can use sodium hypochlorite or calcium hypochlorite granules as the source of chlorine. If the well output is 65 gal/min and the chemical feed pump can inject 100 mL/min at the 50% setting:

1. What is the required strength of the chlorine solution we will feed?
2. What volume of 5.20% sodium hypochlorite will be needed to produce 1 gal of the chlorine feed solution?
3. How many pounds of 65% calcium hypochlorite will be needed to mix each gallon of solution?

Solution:

Step 1: Determine the amount of chlorine to be added to the water (the chlorine dose).

The dose is defined as the chlorine demand of the water, plus the desired residual, or in this case:

$$\text{Dose} = \text{Demand} + \text{Residual}$$

$$= 2.2 \text{ mg/L} + 1.0 \text{ mg/L}$$

$$= 3.2 \text{ mg/L}$$

To obtain a 1.0-mg/L residual when the water enters the distribution system, we must add 3.2 mg/L of chlorine to the water.

Step 2: Determine the strength of the chlorine feed solution that would add 3.2 mg/L of chlorine to 65 gal/min of water when fed at a rate of 100 mL/min.

To make this calculation, consider the diagram of this chlorination system in Figure 17.10. The well pump below is producing water at a flowrate (Q_1) of 65 gal/min with a chlorine concentration (C_1) of 0.0 mg/L. The metering pump will add 100-mL/min (Q_2) of chlorine solution, but we do not know its concentration (C_2) yet. The finished water will have been dosed with a chlorine concentration of 3.2 mg/L (C_1) and will enter the distribution system at a rate (Q_t) of 65 gal + 100 mL/min, with a free residual chlorine concentration of 1.0 mg/L after the chlorine contact time.

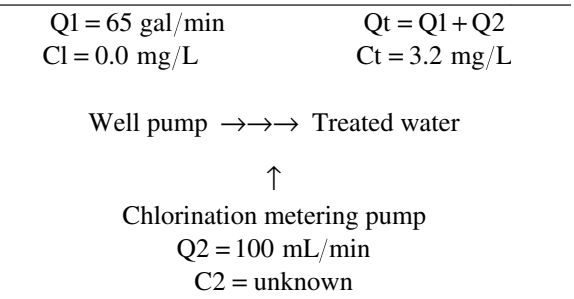

FIGURE 17.10 Chlorination system problem. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Step 3: We must how convert the metering pump flow (100 mL/min) to gallons per minute so we can calculate Q_1.

To do this, we use standard conversion factors:

$$\frac{100 \text{ mL}}{1 \text{ min}} \times \frac{1 \text{ L}}{1000 \text{ mL}} \times \frac{1 \text{ gal}}{3.785 \text{ L}} = 0.026 \text{ gal/min}$$

Now we know that Q_2 is 0.026 gal/min and that Q_t is 65 gal/min + 0.026 gal/min = 65,026 gal/min.

Step 4: We must now use what is known as the stand mass balance equation.

The mass balance equation says that the flow rate times the concentration of the output is equal to the flow rate times the concentration of each of the inputs added together, or in equation form:

$$(Q_1 \times C_1) + (Q_2 \times C_2) = (Q_1 \times C_1)$$

Substituting the numbers given and those we have calculated so far gives us:

$$(65 \text{ gal/min} \times 0.0 \text{ mg/L}) + (0.026 \text{ gal/min} \times \text{mg/L}) =$$

$$(65 \text{ gal/min} + 0.026 \text{ gal/min}) \times 3.2 \text{ mg/L}$$

$$0 + 0.026 \times x = 65.026 \times 3.2$$

$$0.026 \times x = 208.1$$

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$$x = \frac{208.1}{0.026}$$

$$= 8004 \text{ mg/L}$$

This is the answer to the first part of the question, the required strength of the chlorine feed solution. Since a 1% solution is equal to 10,000 mg/L, solution strength of 8,004 mg/L is approximately a 0.80% solution.

To determine the required volume of bleach per gallon to produce this 0.80% solution, we go back to the pounds formula:

$$\text{Pounds} = \text{mg/L} \times 8.34 \times \text{MG}$$

$$= 8004 \text{ mg/L} \times 8.34 \times 0.000001 \text{ MG}$$

$$= 0.067 \text{ lb chlorine/gal solution}$$

Note: Remember to convert gallons to million gallons.

Recalling that the bleach, like water, weighs 8.34 lb/gal and contains approximately 5.20 percent (0.0520) available chlorine:

$$1 \text{ gal bleach} = 8.34 \text{ lb/gal} \times 0.0520$$

$$= 0.43 \text{ lb available chlorine per gallon of bleach}$$

If 1 gal of bleach contains 0.43 lb of available chlorine, how many gallons of bleach do we need to provide the 0.067-lb of chlorine we need for each gallon of chlorine feed solution? To determine the gallons of bleach needed, we use the simple ratio equation:

$$\frac{1 \text{ gal}}{0.443 \text{ lb } Cl_2} = \frac{x \text{ gal}}{0.067 \text{ lb } Cl_2}$$

$$x = \frac{1 \text{ gal} \times 0.067 \text{ lb}}{0.43 \text{ lb}}$$

$$= 0.16 \text{ gal bleach/gal solution}$$

An alternative way to determine the required volume of bleach per gallon to produce this 0.80% solution is to use the solutions equation and calculate it this way:

$$C_1 \times V_1 = C_2 \times V_2$$

$C_1 = 0.80\%$
$V_1 = 1.0$ gal
$C_2 = 5.20\%$
V_2 = unknown

$$0.80\% \text{ solution} \times 1 \text{ gal} = 5.20\% \text{ solution} \times x \text{ gal}$$

$$x = \frac{0.80\% \times 1 \text{ gal}}{5.20\%}$$

$$= 0.15 \text{ gal bleach/gal solution}$$

To summarize, 1 gal of household bleach:

1. Contains 5.20% or 52,000 mg/L available chlorine
2. Equals 0.85 gal of water
3. Equals 0.15 gal available chlorine
4. Weighs 8.34 lb
5. Equals 0.43 available chlorine

The third part of the problem requires that we determine the pounds of calcium hypochlorite needed for each gallon of feed solution. We know that we need 0.066 lb of chlorine for each gallon of solution and that hypochlorite material (HTH) contains 65% available chlorine (i.e., 1.0 lb of HTH contains 0.65 lb of available chlorine). Using the ratio equation:

$$\frac{1 \text{ lb HTH}}{0.65 \text{ lb } Cl_2} = \frac{x \text{ lb HTH}}{0.067 \text{ lb } Cl_2}$$

$$x = \frac{1 \text{ lb} \times 0.067 \text{ lb}}{0.65 \text{ lb}}$$

$$= \frac{0.067}{0.65}$$

$$= 0.1 \text{ lb HTH/gal solution}$$

17.10.11.7 Chlorine Generation

Onsite generation of chlorine has recently become practical. These generation systems, using only salt and electric power, can be designed to meet disinfection and residual standards and to operate unattended at remote sites. Considerations for chlorine generation include cost, concentration of the brine produced, and availability of the process.[54]

17.10.11.7.1 Chlorine

Chlorine gas can be generated by a number of processes, including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of hydrochloric acid. About 70 percent of the chlorine produced in the U.S. is manufactured from the electrolysis of salt brine and caustic solutions in a diaphragm cell.[53] Since chlorine is a stable compound, it is typically produced off-site by a chemical manufacturer. Once produced, chlorine is packaged as a liquefied gas under pressure for delivery to the site in railcars, tanker trucks, or cylinders.

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TABLE 17.19
Chlorine Uses and Doses

Application	Typical Dose	Optimal pH	Reaction Time	Effectiveness	Other Considerations
Iron	0.62 mg/mg Fe	7.0	Less than 1 h	Good	
Manganese	0.77 mg/mg Mn	7–8	1–3 h	Slow kinetics	Reaction time increases at lower pH
		9.5	Minutes		
Biological growth	1–2 mg/L	6–8	N/A[a]	Good	DBP Formation
Taste/odor	Varies	6–8	Varies	Varies	Effectiveness depends on compound
Color removal	Varies	4.0–6.8	Minutes	Good	DBP Formation
Zebra mussels	2–5 mg/L		Shock level	Good	DBP Formation
	0.2–0.5 mg/L		Maintenance level		
Asiatic clams	0.3–0.5 mg/L		Continuous	Good	DBP Formation

[a] N/A = not available.

Source: Adapted in part from White, G.C., in *Handbook of Chlorination and Alternative Disinfectants*, Van Nostrand Reinhold, New York, 1992; Connell, G.F., in *The Chlorination/Chloramination Handbook*, Denver, CO, American Water Works Association, 1996; Culp, Wesner, and Culp, *Handbook of Public Water Systems*, Van Nostrand Reinhold, New York, 1986. With permission.

17.10.11.7.2 Sodium Hypochlorite

Dilute sodium hypochlorite solutions (less than 1%) can be generated electrochemically on-site from salt brine solution. Typically, sodium hypochlorite solutions are referred to as liquid bleach or Javelle water. Generally, the commercial or industrial grade solutions produced have hypochlorite strengths of 10 to 16%. The stability of sodium hypochlorite solution depends on the hypochlorite concentration, the storage temperature, the length of storage (time), the impurities of the solution, and exposure to light. Decomposition of hypochlorite over time can affect the feed rate and dosage, as well as produce undesirable by-products such as chlorite ions or chlorate.[55]

Because of the storage problems, many systems are investigating on-site generation of hypochlorite in lieu of its purchase from a manufacturer or vendor.[56]

17.10.11.7.3 Calcium Hypochlorite

To produce calcium hypochlorite, HOCl is made by adding chlorine monoxide to water and then neutralizing it with lime slurry to create a solution of calcium hypochlorite. Generally, the final product contains up to 70% available chlorine and 4 to 6% lime. Storage of calcium hypochlorite is a major safety consideration. It should never be stored where it is subject to heat or allowed to contact any organic material of an easily oxidized nature.[56]

17.10.11.8 Primary Uses and Points of Application of Chlorine

17.10.11.8.1 Uses

The main usage of chlorine in drinking water treatment is for disinfection. However, chlorine has also found application for a variety of other water treatment objectives such as, the control of nuisance organisms, oxidation of taste and odor compounds, oxidation of iron and manganese, color removal, and as a general treatment aid to filtration and sedimentation processes.[57] Table 17.19 presents a summary of chlorine uses and doses.[58]

TABLE 17.20
Typical Chlorine Points of Application

Point of Application
Raw water intake
Flash mixer (prior to sedimentation)
Filter influent
Filter clearwell
Distribution System

Source: Adapted in part from White, G.C., in *Handbook of Chlorination and Alternative Disinfectants*, Van Nostrand Reinhold, New York, 1992; Connell, G.F., in *The Chlorination/Chloramination Handbook*, Denver, CO, American Water Works Association, 1996; American Water Works Association, *Water Quality and Treatment*, Pontius, F.W., Ed., McGraw-Hill, New York, 1990. With permission.

17.10.11.8.2 Points of Application

At conventional surface water treatment plants, chlorine is typically added for prechlorination at either the raw water intake or flash mixer, for intermediate chlorination ahead of the filters, for postchlorination at the filter clearwell, or for rechlorination of the distribution system.[58] Table 17.20 summarizes typical points of application.

17.10.11.8.3 Typical Doses

Table 17.21 shows the typical dosages for the various forms of chlorine. The wide range of chlorine gas dosages most likely represents its use as both an oxidant and a disinfectant. While sodium hypochlorite and calcium

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TABLE 17.21
Typical Chlorine Dosages at Water Treatment Plants

Chlorine Compound	Range of Doses
Calcium hypochlorite	0.6–5 mg/L
Sodium hypochlorite	0.2–2 mg/L
Chlorine gas	1–16 mg/L

Source: Science Applications International Corporation, as adapted from EPA's review of public water systems' initial sampling plans that were required by EPA's Information Collection Rule, 1998. With permission.

hypochlorite can also serve as both an oxidant and a disinfectant, their higher cost may limit their use.

17.10.11.9 Factors Affecting Chlorination

Disinfection by chlorination is a rather straightforward process, but several factors (interferences) can affect the ability of chlorine to perform its main function: disinfection.

Turbidity is one such interference. As we described earlier, turbidity is a general term that describes particles suspended in the water. Water with a high turbidity appears cloudy. Turbidity interferes with disinfection when microorganisms "hide" from the chlorine within the particles causing turbidity. This problem is magnified when turbidity comes from organic particles, such as those from sewage effluent. To overcome this, the length of time the water is exposed to the chlorine or the chlorine dose must be increased, although highly turbid waters may still shield some microorganisms from the disinfectant.

EPA took this type of problem into consideration in its SWTR and the 1996 IESWTR that tightens controls on DBPs and turbidity and regulates *cryptosporidium*. The rule requires continuous turbidity monitoring of individual filters and tightens allowable turbidity limits for combined filter effluent, cutting the maximum from 5 ntu to 1 ntu and the average monthly limit from 0.5 to 0.3 NTU.

Note: Recall that IESWTR applies to large (those serving more than 10,000 people) public water systems that use surface water or groundwater directly influenced by surface water and is the first to directly regulate *cryptosporidium*.

Temperature affects the solubility of chlorine, the rate at which disinfecting ions are produced, and the proportion of highly effective forms of chlorine that will be present in the water. More importantly, temperature affects the rate at which the chlorine reacts with the microorganisms. As water temperature decreases, the rate at which the chlorine can pass through the microorganisms' cell wall decreases, making the chlorine less effective as a disinfectant.

Along with the presence of turbidity-causing agents, such as suspended solids and organic matter, chemical compounds in the water may influence chlorination. These include high alkalinity, nitrates, manganese, iron, and hydrogen sulfide.

17.10.11.10 Measuring Chlorine Residual

During normal operations, waterworks operators perform many operating checks and tests on unit processes throughout the plant. One of the most important and most frequent operating checks is chlorine residual test. This test must be performed whenever a distribution sample is collected for microbiological analysis. It should be done frequently where the treatment facility discharges to the water distribution system to ensure that the disinfection system is working properly.

In testing for chlorine residual, several methods are available. The most common and most convenient is the DPD color comparator method. This method uses a small portable test kit with prepared chemicals that produce a color reaction indicating the presence of chlorine. By comparing the color produced by the reaction with a standard, we can determine the approximate chlorine residual concentration of the sample. DPD color comparator chlorine residual test kits are available from the manufacturers of chlorination equipment.

Note: The color comparator method is acceptable for most groundwater systems and for chlorine residual measurements in the distribution system. Keep in mind that the methods used to take chlorine residual measurements for controlling the disinfection process in surface water systems and some groundwater systems where adequate disinfection is essential must be approved by standard methods.

17.10.11.11 Pathogen Inactivation and Disinfection Efficacy

17.10.11.11.1 Inactivation Mechanisms

Research has shown that chlorine is capable of producing lethal events at or near the cell membrane as well as affecting DNA. In bacteria, chlorine was found to adversely affect cell respiration, transport, and possibly DNA activity.[59] Chlorination was found to cause an immediate decrease in oxygen utilization in both *E. coli* and *Candida parapsilosis* studies. The results also found that chlorine damages the cell wall membrane, promotes leakage through the cell membrane, and produces lower levels of DNA synthesis for *E. coli*, *Candida parapsilosis*, and *Mycobacterium fortuitum* bacteria. This study also showed that chlorine inactivation is rapid and does not

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require bacteria reproduction.[59] These observations rule out mutation or lesions as the principal inactivation mechanisms since these mechanisms require at least one generation of replication for inactivation to occur.

17.10.11.11.2 Environmental Effects

Several environmental factors influence the inactivation efficiency of chlorine, including water temperature, pH, contact time, mixing, turbidity, interfering substances, and the concentration of available chlorine. In general, the highest levels of pathogen inactivation are achieved with high chlorine residuals, long contact times, high water temperature, and good mixing, combined with a low pH, low turbidity, and the absence of interfering substances. Of the environmental factors, pH and temperature have the most impact on pathogen inactivation by chlorine. The effect of pH and temperature on pathogen inactivation is discussed below.

17.10.11.11.2.1 pH

The germicidal efficiency of HOCl is much higher than OCl^-. The distribution of chlorine species between HOCl and OCl^- is determined by pH. Because HOCl dominates at low pH, chlorination provides more effective disinfection at low pH. At high pH, OCl^- dominates, which causes a decrease in disinfection efficiency.

The inactivation efficiency of gaseous chlorine and hypochlorite is the same at the same pH after chlorine addition. The addition of gaseous chlorine will decrease the pH, while the addition of hypochlorite will increase the pH of the water. Therefore, without pH adjustment to maintain the same treated water pH, gaseous chlorine will have greater disinfection efficiency than hypochlorite.

The impact of pH on chlorine disinfection has been demonstrated in the field. For example, virus inactivation studies have shown that 50% more contact time is required at a pH of 7.0 than at a pH of 6.0 to achieve comparable levels of inactivation. These studies also demonstrated that a rise in pH from 7.0 to 8.8 or 9.0 requires 6 times the contact time to achieve the same level of virus inactivation.[60] Although these studies found a decrease in inactivation with increasing pH, some studies have shown the opposite effect. A 1972 study reported that viruses were more sensitive to free chorine at high pH than at low pH.[61]

17.10.11.11.2.2 Temperature

For typical drinking water treatment temperatures, pathogen inactivation increases with temperature. Virus studies indicated that the contact time should be increased by two to three times to achieve comparable inactivation levels when the water temperature is lowered by 10°C.[62]

17.10.11.11.3 Disinfection Efficacy

Since its introduction, numerous investigations have been made to determine the germicidal efficiency of chlorine. Although there are widespread differences in the susceptibility of various pathogens, the general order of increasing chlorine disinfection difficulty are bacteria, viruses, and protozoa.

17.10.11.11.3.1 Bacteria Inactivation

Chlorine is an extremely effective disinfectant for inactivating bacteria. A study conducted during the 1940s investigated the inactivation levels as a function of time for *E. coli*, *Pseudomonas aeruginosa*, *Salmonella typhi*, and *Shigella dysenteriae*.[63] Study results indicated that HOCl is more effective than OCl^- for inactivation of these bacteria. These results have been confirmed by several researchers that concluded that HOCl is 70 to 80 times more effective than OCl^- for inactivating bacteria.[64]

17.10.11.11.3.2 Virus Inactivation

Chlorine has been shown to be a highly effective viricide. One of the most comprehensive virus studies was conducted in 1971 using treated Potomac Estuary water.[65] The tests were performed to determine the resistance of 20 different enteric viruses to free chlorine under constant conditions of 0.5 mg/L free chlorine and a pH and temperature of 7.8 and 2°C, respectively. In this study, the least resistant virus was found to be reovirus and required 2.7 min to achieve 99.99% inactivation (4-log removal). The most resistant virus was found to be a poliovirus, which required more than 60 min for 99.99% inactivation. The corresponding CT range required to achieve 99.99 percent inactivation for all 20 viruses was between 1.4 to over 30 mg · min/L.

Virus survival studies have also been conducted on a variety of both laboratory and field strains.[66] All of the virus inactivation tests in this study were performed at a free chlorine residual of 0.4 mg/L; a pH of 7.0; a temperature of 5°C; and contact times of either 10, 100, or 1000 min. Test results showed that of the 20 cultures tested only 2 poliovirus strains reached 99.99% inactivation after 10 min (CT = 4 mg · min/L), and 6 poliovirus strains reached 99.99% inactivation after 100 min (CT = 40 mg · min/L). In addition, 11 of the 12 polioviruses plus 1 coxsackievirus strain (12 out of a total of 20 viruses) reached 99.99% inactivation after 1000 min (CT = 400 mg · min/L).

17.10.11.11.3.3 Protozoa Inactivation

Chlorine has been shown to have limited success inactivating protozoa. Data obtained during a 1984 study indicated that the resistance of giardia cysts is two orders of magnitude higher than that of enteroviruses and more than three orders of magnitude higher than the enteric bacteria.[67] CT requirements for giardia cysts inactivation when using chlorine as a disinfectant has been determined for various pH and temperature conditions.[68] The CT values increase at low temperatures and high pH.

Chlorine has little impact on the viability of *cryptosporidium* oocysts when used at the relatively low doses encountered in water treatment (e.g., 5 mg/L). Approximately 40% removals (0.2 log) of *cryptosporidium* were achieved at CT values of both 30 and 3600 mg · min/L.[69]

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Another study determined that "no practical inactivation was observed" when oocysts were exposed to free chlorine concentrations ranging from 5 to 80 mg/L at a pH of 8, a temperature of 22°C, and contact times of 48 to 245 min.[70]

CT values ranging from 3000 to 4000 mg · min/L were required to achieve 1 log of *cryptosporidium* inactivation at a pH of 6.0 and a temperature of 22°C. During this study, one trial in which oocysts were exposed to 80 mg/L of free chlorine for 120 min was found to produce greater than 3 logs of inactivation.

17.10.11.12 Disinfection By-Products

Halogenated organics are formed when NOM reacts with free chlorine or free bromine. Free chlorine is normally introduced into water directly as a primary or secondary disinfectant. Free bromine results from the oxidation by chlorine of the bromide ion in the source water. Factors affecting the formation of these halogenated DBPs include type and concentration of NOM, chlorine form and dose, time, bromide ion concentration, pH, organic nitrogen concentration, and temperature. Organic nitrogen significantly influences the formation of nitrogen containing DBPs, including haloacetonitriles,[34] halopicrins, and cyanogen halides.

Since most water treatment systems have been required to monitor for TTHMs in the past, most water treatment operators are probably familiar with some of the requirements that the Disinfectant/Disinfection By-Product (D/DBP) Rule involve. The key points of the DBP Rule and some of the key changes water supply systems are required to comply with are summarized below.

17.10.11.12.1 Chemical Limits and Testing

1. Testing requirements will include TTTHMs and five haloacetic acids (HAA5). The MCL for TTHM is 0.080 mg/L for surface water systems. In addition, a new MCL of 0.060 mg/L has been established for HAA5.
2. New MCLs have been established for bromate (0.010 mg/L and chlorite (1.0 mg/L). Bromate monitoring is required of systems that use ozone. Chlorite monitoring only will be required of systems that use chlorine dioxide (i.e., sodium- and calcium hypochlorite are not included).
3. MRDLs will be established for total chlorine (4.0 mg/L) and chlorine dioxide (0.8 mg/L).

17.10.11.12.2 Operational Requirements

Analytical requirements for measuring chlorine residual have been changed to require digital equipment (i.e., no color wheels or analog test kits). The test kit must have a detection limit of at least 0.1 mg/L.

17.10.11.12.3 Monitoring and Reporting

(Note: Individual state requirements will differ, but at the minimum the following requirements are listed.)

1. Surface water system monitoring requirements include four quarterly samples per treatment plant (source treatment unit) for TTHM and HAA5. One of these quarterly samples, or 25% of the total samples, must be collected at the maximum residence time location. The remaining samples must be collected at representative locations throughout the entire distribution system. Compliance is based on a running annual average computed quarterly.
2. For those surface water systems using conventional filtration or lime softening, a D/DBP monthly operating report TOC removal will be required to be completed and filed with state EPA. This report will include TOC, alkalinity, and SUVA parameters. There will be an additional monthly operating report for bromate, chlorite, chlorine dioxide, and chlorine residual. More information will be forthcoming closer to the compliance date.
3. TTHM monitoring results may indicate the possible need for additional treatment to include best available technology for reduction of DBP. This may include GAC, enhanced coagulation (for surface water systems using conventional filtration), or enhanced softening (for systems using lime softening).
4. Operators are required to develop and implement a sample-monitoring plan for disinfectant residual and disinfection by-products. The plan will be required to be submitted to and approved by state EPA. Disinfection residual monitoring compliance for total chlorine, including chloramines, will be based upon a running annual average, computed quarterly, of the monthly average of all samples collected under this rule. Disinfectant residual monitoring compliance for chlorine dioxide will be based upon consecutive daily samples. Disinfectant residual monitoring will be required at the same distribution point and time as total coliform monitoring. In addition, if the operator feeds ozone or chlorine dioxide, a sample monitoring plan for bromate or chlorite, respectively, must be submitted to and approved by state EPA.

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17.10.11.13 Operational Considerations

17.10.11.13.1 Application Methods

Different application methods are used, depending upon the form of chlorine. The following paragraphs describe the typical application methods for chlorine, sodium hypochlorite, and calcium hypochlorite.

17.10.11.13.1.1 Chlorine

Liquefied chlorine gas is typically evaporated to gaseous chlorine prior to metering. The heat required for evaporation can be provided through either a liquid chlorine evaporator or the ambient heat input to the storage container. Once the compressed liquid chlorine is evaporated, chlorine gas is typically fed under vacuum conditions. Either an injector or a vacuum induction mixer usually creates the required vacuum. The injector uses water flowing through a venturi to draw the chlorine gas into a side stream of carrier water to form a concentrated chlorine solution. This solution is then introduced into the process water through a diffuser or mixed with a mechanical mixer. A vacuum induction mixer uses the motive forces of the mixer to create a vacuum and draws the chlorine gas directly into the process water at the mixer.

17.10.11.13.1.2 Sodium Hypochlorite

Sodium hypochlorite solutions degrade over time. For example, a 12.5% hypochlorite solution will degrade to 10% in 30 d under best case conditions.[53] Increased temperature, exposure to light, and contact with metals increase the rate of sodium hydroxide degradation.[58]

Sodium hypochlorite solution is typically fed directly into the process water using a type of metering pump. Similar to chlorine solution, sodium hypochlorite is mixed with the process water with either a mechanical mixer or induction mixer. Sodium hypochlorite solution is typically not diluted prior to mixing to reduce scaling problems.

17.10.11.13.1.3 Calcium Hypochlorite

Commercial high-level calcium hypochlorite contains at least 70% available chlorine.[71] Under normal storage conditions, calcium hypochlorite loses 3 to 5% of its available chlorine in a year.[54] Calcium hypochlorite comes in powder, granular, and compressed tablet forms.[71] Typically, calcium hypochlorite solution is prepared by mixing powdered or granular calcium hypochlorite with a small flow. The high-chlorinated solution is then flow paced into drinking water flow.

17.10.11.13.2 Safety and Handling Considerations

17.10.11.13.2.1 Chlorine

Chlorine gas is a strong oxidizer. The U.S. Department of Transportation classifies chlorine as a poisonous gas.[58] Fire codes typically regulate the storage and use of chlorine. In addition, facilities storing more than 2500 lb of chlorine are subject to the following two safety programs:

1. Process Safety Management standard regulated by the Occupational Safety and Health Administration under 29 CFR 1910.119.
2. The Risk Management Program Rule administered by EPA under Section 112 (r) of the Clean Air Act.

All of these regulations (as well as local and state codes and regulations) must be considered during the design and operation of chlorination facilities at a water treatment plant.

17.10.11.13.2.2 Sodium Hypochlorite

Sodium hypochlorite solution is a corrosive liquid with an approximate pH of 12.[10]Therefore, typical precautions for handling corrosive materials such as avoiding contact with metals, including stainless steel, should be used.

Sodium hypochlorite solutions may contain chlorate. Chlorate is formed during the both the manufacturing and storage of sodium hypochlorite (due to degradation of the product). Chlorate formation can be minimized by reducing the degradation of sodium hypochlorite by limiting storage time, avoiding high temperatures, and reducing light exposure.[55]

Spill contaminant must be provided for the sodium hypochlorite storage tanks. Typical spill containment structures include containment for the entire contents of the largest tank (plus freeboard for rainfall or fire sprinklers), no uncontrolled floor drains, and separate containment areas for each incompatible chemical.

17.10.11.13.2.3 Calcium Hypochlorite

Calcium hypochlorite is an oxidant and should be stored separately from organic materials that can be readily oxidized. It should also be stored away from sources of heat. Improperly stored calcium hypochlorite has caused spontaneous combusting fires.

17.10.11.14 Advantages and Disadvantages of Chlorine Use

The following list presents selected advantages and disadvantages of using chlorine as a disinfection method for drinking water.[72] Because of the wide variation of system size, water quality, and dosages applied, some of these advantages and disadvantages may not apply to a particular system.

Advantages

1. Oxidizes soluble iron, manganese, and sulfides.
2. Enhances color removal.
3. Enhances taste and odor.
4. May enhance coagulation and filtration of particulate contaminants.
5. Is an effective biocide

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TABLE 17.22
Summary of Chlorine Disinfection

Consideration	Description
Generation	Chlorination may be performed using chlorine gas or other chlorinated compounds that may be in liquid or solid form. Chlorine gas can be generated by a number of processes including the electrolysis of alkaline brine or hydrochloric acid, the reaction between sodium chloride and nitric acid, or the oxidation of hydrochloric acid. Since chlorine is a stable compound, chlorine gas, sodium hypochlorite, and calcium hypochlorite are typically produced off-site by a chemical manufacturer.
Primary uses	The primary use of chlorination is disinfection. Chlorine also serves as an oxidizing agent for taste and odor control, prevention of algal growths, maintaining clear filter media, removal of iron and manganese, destruction of hydrogen sulfide, color removal, maintaining the water quality at the distribution systems, and improving coagulation.
Inactivation efficiency	The general order of increasing chlorine disinfection difficulty is bacteria, viruses, and then protozoa. Chlorine is an extremely effective disinfectant for inactivating bacteria and highly effective viricide. However, chlorine is less effective against giardia cysts. Cryptosporidium oocysts are highly resistant to chlorine.
By-product formation	When added to the water, free chlorine reacts with NOM and bromide to form DBPs, primarily THMs, some HAAs, and others.
Point of application	Raw water storage, precoagulation/postraw water storage, presedimentation/postcoagulation, post-sedimentation/prefiltration, post filtration (disinfection), or in the distribution system.
Special considerations	Because chlorine is such a strong oxidant and extremely corrosive, special storage and handling considerations should be considered in the planning of a water treatment plant. Additionally, health concerns associated with handling and use of chlorine is an important consideration.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

6. Is the easiest and least disinfection method, regardless of system size
7. Is the most widely used disinfection method, and therefore, the best known
8. Is available as calcium and sodium hypochlorite. Use of these solutions is more advantageous for smaller systems than chlorine gas because they are easier to use, safer, and need less equipment compared to chlorine gas.
9. Provides a residual.

Disadvantages

1. May cause a deterioration in coagulation and filtration of dissolved organic substances.
2. Forms halogen-substituted by-products.
3. Finished water could have taste and odor problems, depending on the water quality and dosage.
4. Chlorine gas is a hazardous corrosive gas.
5. Special leak containment and scrubber facilities could be required for chlorine gas.
6. Typically, sodium and calcium hypochlorite are more expensive than chlorine gas.
7. Sodium hypochlorite degrades over time and with exposure to light.
8. Sodium hypochlorite is a corrosive chemical.
9. Calcium hypochlorite must be stored in a cool, dry place because of its reaction with moisture and heat.
10. A precipitate may form in a calcium hypochlorite solution because of impurities, therefore, an antiscalant chemical may be needed.
11. Higher concentrations of hypochlorite solutions are unstable and will produce chlorate as a by-product.
12. Chlorine use is less effective at high pH.
13. Chlorine forms oxygenated by-products that are biodegradable and can enhance subsequent biological growth if a chlorine residual is not maintained.
14. Chlorine releases constituents bound in the distribution system (e.g., arsenic) by changing the redox state.

17.10.11.15 Chlorine Summary Table

Table 17.22 presents a summary of the considerations for the use of chlorine as a disinfectant.

17.11 ARSENIC REMOVAL FROM DRINKING WATER

(Note: Much of the following information is based on EPA's *Technologies and Costs for Removal of Arsenic from Drinking Water*, EPA 815-R-00–028, @ www.epa.gov/safewater, accessed November 4, 2002.)

Operators may be familiar with the controversy created when newly elected President George W. Bush placed

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the pending Arsenic Standard on temporary hold. Bush prevented implementation of the Arsenic Standard to give scientists time to review the standard, take a closer look at the possible detrimental effects on health and well-being of consumers in certain geographical areas of the U.S., and give economists time to determine the actual cost of implementation.

As mentioned, Bush's decision caused quite a stir, especially among environmentalists, the media, and others who felt that the Arsenic Standard should be enacted immediately to protect affected consumers. Bush, who understood the emotional and political implications of shelving the Arsenic Standard, also understood the staggering economical implications involved in implementing the new, tougher standard. Many view Bush's decision as the wrong one. Others view his decision as the right one; they base their opinion on the old adage, "It is best to make scientific judgements based on good science instead of on 'feel good' science."

Whether the reader shares the latter view or not, the point is that arsenic levels in potable water supplies are required to be reduced to a set level and in the future will have to be reduced to an even lower level. Accordingly, water treatment plants affected by the existing arsenic requirements and the pending tougher arsenic requirements should be familiar with the technologies for removal of arsenic from water supplies. In this section, we describe a number of these technologies.

17.11.1 Arsenic and Water

Arsenic is a naturally occurring element present in food, water, and air. Known for centuries to be an effective poison, some animal studies suggest that arsenic may be an essential nutrient at low concentrations. Non-malignant skin alterations, such as keratosis and hypo- and hyperpigmentation, have been linked to arsenic ingestion, and skin cancers have developed in some patients. Additional studies indicate that arsenic ingestion may result in internal malignancies, including cancers of the kidney, bladder, liver, lung, and other organs. Vascular system effects have also been observed, including peripheral vascular disease, which in its most severe form, results in gangrene or Blackfoot disease. Other potential effects include neurologic impairment.[73]

The primary route of exposure to arsenic for humans is ingestion. Exposure via inhalation is considered minimal, though there are regions where elevated levels of airborne arsenic occur periodically.[74] Arsenic occurs in two primary forms: organic and inorganic. Organic species of arsenic are predominately found in foodstuffs, such as shellfish, and include such forms as monomethyl arsenic acid, dimethyl arsenic acid, and arseno-sugars. Inorganic arsenic occurs in two valence states: arsenite and arsenate. In natural surface waters arsenate is the dominant species.

17.11.2 Arsenic Removal Technologies

Arsenic removal technologies are discussed in this section. Some of these technologies are traditional treatment processes that have been tailored to improve removal of arsenic from drinking water. Several treatment techniques discussed here are at the experimental stage with regard to arsenic removal, and some have not been demonstrated at full scale. Although some of these processes may be technically feasible, their cost may be prohibitive.

Technologies discussed in this section are grouped into four broad categories: prescriptive processes, adsorption processes, ion exchange processes, and separation (membrane) processes. Each category is discussed here, with at least one treatment technology described in each category.

17.11.2.1 Prescriptive Processes

17.11.2.1.1 Coagulation and Filtration

As mentioned, coagulation and flocculation is a treatment process by which the physical or chemical properties of dissolved chemical properties of dissolved colloidal or suspended matter are altered such that agglomeration is enhanced to an extent that the resulting particles will settle out of solution by gravity or will be removed by filtration. Coagulants change surface charge properties of solids to allow agglomeration and enmeshment of particles into a flocculated precipitate. In either case, the final products are larger particles, or floc, that more readily filter or settle under the influence of gravity.

The coagulation and filtration process has traditionally been used to remove solids from drinking water supplies. However, the process is not restricted to the removal of particles. Coagulants render some dissolved species (e.g., NOM, inorganics, and hydrophobic synthetic organic compounds) insoluble, and the metal hydroxide particles produced by the addition of metal salt coagulants (typically aluminum sulfate, ferric chloride, or ferric sulfate) can adsorb other dissolved species. Major components of a basic coagulation and filtration facility include chemical feed systems, mixing equipment, basins for rapid mix, flocculation, settling, filter media, sludge handling equipment, and filter backwash facilities. Settling may not be necessary in situations where the influent particle concentration is very low. Treatment plants without settling are known as direct filtration plants.

17.11.2.1.2 Iron and Manganese Oxidation

Iron and manganese oxidation is commonly used by facilities treating groundwater. The oxidation process used to remove iron and manganese leads to the formation of hydroxides that remove soluble arsenic by precipitation or adsorption reactions.

Arsenic removal during iron precipitation is fairly efficient.[75] Removal of 2 mg/L of iron achieves a 92.5%

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removal of arsenic from a 10 µg/L arsenate initial concentration by adsorption alone. Even removal of 1 mg/L of iron resulted in the removal of 83% of influent arsenic from a source with 22-µg/L arsenate. Indeed, field studies of iron removal plants have indicated that this treatment can feasibly reach 3 g/L. However, the removal efficiencies achieved by iron removal are not as high or as consistent as those realized by activated alumina or ion exchange.

Note, however, that arsenic removal during manganese precipitation is relatively ineffective when compared to iron even when removal by both adsorption and coprecipitation are considered. For instance, precipitation of 3-mg/L manganese removed only 69% of arsenate of a 12.5-µg/L arsenate influent concentration.

Oxidation filtration technologies may be effective arsenic removal technologies. Research of oxidation filtration technologies has primarily focused on greensand filtration. As a result, the following discussion focuses on the effectiveness of greensand filtration as an arsenic removal technology.

Substantial arsenic removal has been seen using greensand filtration.[76] The active material in greensand is glauconite, a green, iron-rich, clay-like mineral that has ion exchange properties. Glauconite often occurs in nature as small pellets mixed with other sand particles, giving a green color to the sand. The glauconite sand is treated with potassium permanganate until the sand grains are coated with a layer of manganese oxides, particularly manganese dioxide. The principle behind this arsenic removal treatment is multifaceted and includes oxidation, ion exchange, and adsorption. Arsenic compounds displace species from the manganese oxide (presumably OH^- and H_2O), becoming bound to the greensand surface — in effect an exchange of ions. The oxidative nature of the manganese surface converts arsenite to arsenate and arsenate is adsorbed to the surface. As a result of the transfer of electrons and adsorption of arsenate, reduced manganese is released from the surface.

The effectiveness of greensand filtration for arsenic filtration for arsenic removal is dependent on the influent water quality. Surmanian et al. showed a strong correlation between influent iron concentration and arsenic percent removal. Removal increased from 41 to more than 80% as the iron-arsenic ratio increased from 0 to 20 when treating a tap water with a spiked arsenite concentration of 200 mg/L. The tap water contained 366-mg/L sulfate and 321 mg/L total dissolved solids; neither constituent seemed to affect arsenic removal. The authors also point out that the influent manganese concentration may play an important role. Divalent ions, such as calcium, can also compete with arsenic for adsorption sites. Water quality would need to be carefully evaluated for applicability for treatment using greensand. Other researchers have also reported substantial arsenic removal using this technology, including arsenic removals of greater than 90% for treatment of groundwater.[76]

As with other treatment media, greensand must be regenerated when its oxidative and adsorptive capacity has been exhausted. Greensand filters are regenerated using a solution of excess potassium permanganate. Like other treatment media, the regeneration frequency will depend on the influent water quality in terms of constituents that will degrade the filter capacity. Regenerant disposal for greensand filtration has not been addressed in previous research.

17.11.2.1.3 Coagulation Assisted Microfiltration

Arsenic is removed effectively by the coagulation process. Microfiltration is used as a membrane separation process to remove particulates, turbidity, and microorganisms. In coagulation assisted microfiltration technology, microfiltration is used in a manner similar to a conventional gravity filter. The advantages of microfiltration over conventional filtration are outlined below:[77]

1. Microorganism barrier is more effective during coagulation process upsets.
2. Smaller floc sizes can be removed (smaller amounts of coagulants are required).
3. Total plant capacity is increased.

Vickers et al. reported that microfiltration exhibited excellent arsenic removal capability.[78] This report is corroborated by pilot studies conducted by Clifford, which found that coagulation assisted microfiltration could reduce arsenic levels below 2 g/L in waters with a pH of between 6 and 7, even when the influent concentration of irion is approximately 2.5 mg/L.[79] These studies also found that the same level of arsenic removal could be achieved by this treatment process even if source water sulfate and silica levels were high. Coagulation assisted microfiltration can also reduce arsenic levels to an even greater extent at a slightly lower pH (approximately 5.5).

The addition of a coagulant did not significantly affect the membrane-cleaning interval, although the solids level to the membrane system increased substantially. With an iron and manganese removal system, it is critical that all of the iron and manganese be fully oxidized before they reach the membrane to prevent fouling.[77]

17.11.2.1.4 Enhanced Coagulation

The D/DBP Rule requires the use of enhanced coagulation treatment for the reduction of DBP precursors for surface water systems that have sedimentation capabilities. The enhanced process involves modifications to the existing coagulation process such as increasing the coagulant dosage, reducing the pH, or both.

Cheng et al. conducted bench, pilot, and demonstration scale studies to examine arsenate removals during

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enhanced coagulation.[80] The enhanced coagulation conditions in these studies included an increase of alum and ferric chloride coagulant dosage from 10 to 30 mg/L, a decrease of a pH from 7 to 5.5, or both. Results from these studies indicated the following:

1. More than 90% arsenate removal can be achieved under enhanced coagulation conditions. Arsenate removals above 90% were easily attained under all conditions when ferric chloride was used.
2. Enhanced coagulation using ferric salts is more effective for arsenic removal than enhanced coagulation using alum. With an influent arsenic concentration of 5 µg/L, ferric chloride achieved 96% arsenate removal with a dosage of 10 mg/L and no acid addition. When alum was used, 90% arsenate removal could not be achieved without reducing the pH.
3. Lowering pH during enhanced coagulation improved arsenic removal by alum coagulation. With ferric coagulation pH does not have a significant effect between 5.5 and 7.0.

Note: Posttreatment pH adjustment may be required for corrosion control when the process is operated at a low pH.

17.11.2.1.5 Lime Softening

Recall that hardness is predominately caused by calcium and magnesium compounds in solution. Lime softening removes this hardness by creating a shift in the carbonate equilibrium. The addition of lime to water raises the pH. Bicarbonate is converted to carbonate as the pH increases, and as a result, calcium is precipitated as calcium carbonate. Soda ash (sodium carbonate) is added if insufficient bicarbonate is present in the water to remove hardness to the desired level. Softening for calcium removal is typically accomplished at a pH range of 9 to 9.5. For magnesium removal, excess lime is added beyond the point of calcium carbonate precipitation. Magnesium hydroxide precipitates at pH levels greater than 10.5. Neutralization is required if the pH of the softened water is excessively high (above 9.5) for potable use. The most common form of pH adjustment in softening plants is recarbonation with carbon dioxide.

Lime softening has been widely used in the U.S. for reducing hardness in large water treatment systems. Lime softening, excess lime treatment, split lime treatment, and lime-soda softening are all common in municipal water systems. All of these treatment methods are effective in reducing arsenic. Arsenite or arsenate removal is pH dependent. Oxidation of arsenite is the predominant form. Considerable amounts of sludge are produced in a lime softening system and its disposal is expensive. Large capacity systems may find it economically feasible to install recalcination equipment to recover the reuse of lime sludge and reduce disposal problems. Construction of a new lime softening plant for the removal of arsenic would not generally be recommended unless hardness was also reduced.

17.11.2.2 Adsorptive Processes

17.11.2.2.1 Activated Alumina

Activated alumina is a physical and chemical process by which ions in the feed water are sorbed to the oxidized activated alumina surface. Activated alumina is considered an adsorption process, although the chemical reactions involved are actually an exchange of ions.[81] Activated alumina is prepared through dehydration of $Al(OH)_3$ at high temperatures, and consists of amorphous and gamma alumina oxide.[82]

Activated alumina is used in packed beds to remove contaminants such as fluoride, arsenic, selenium, silica, and NOM. Feed water is continuously passed through the bed to remove contaminants. The contaminant ions are exchanged with the surface hydroxides on the alumina. When adsorption sites on the activated alumina surface become filled, the bed must be regenerated. Regeneration is accomplished through a sequence of rinsing with regenerant, flushing with water, and neutralizing with acid. The regenerant is a strong base that is typically sodium hydroxide; the neutralizer is a strong acid that is typically sulfuric acid.

Many studies have shown that activated alumina is an effective treatment technique for arsenic removal. Factors such as pH, arsenic oxidation state, competing ions, empty bed contact time, and regeneration have significant effects on the removals achieved with activated alumina. Other factors include spent regenerant disposal, alumina disposal, and secondary water quality.

17.11.2.2.2 Ion Exchange

Ion exchange is a physical and chemical process by which an ion on the solid phase is exchanged for an ion in the feed water. This solid phase is typically a synthetic resin that has been chosen to preferentially adsorb the particular contaminant of concern. To accomplish this exchange of ions, feed water is continuously passed through a bed of ion exchange resin beads in a downflow or upflow mode until the resin is exhausted. Exhaustion occurs when all sites on the resin beads have been filled by contaminant ions. At this point, the bed is regenerated by rinsing the ion exchange column with a regenerant — a concentrated solution of ions initially exchanged from the resin. The number of bed volumes (BVs) that can be treated before exhaustion varies with resin type and influent water quality. Typically from 300 to 60,000 BV can be treated before regeneration is required. In most cases, regeneration of

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the bed can be accomplished with only 1 to 5 BV of regenerant followed by 2 to 20 BV of rinse water.

Important considerations in the applicability of the ion exchange process for removal of a contaminant include water quality parameters such as pH, competing ions, resin type, alkalinity, and influent arsenic concentration. Other factors include the affinity of the resin for the contaminant, spent regenerant and resin disposal requirements, secondary water quality effects, and design operating parameters.

17.11.2.3 Membrane Processes

Membranes are a selective barrier, allowing some constituents to pass while blocking the passage of others. The movement of constituents across a membrane requires a driving force (i.e., a potential difference between the two sides of the membrane). Membrane processes are often classified by the type of driving force, including pressure, concentration, electrical potential, and temperature. The processes discussed here include only pressure-driven and electrical potential-driven types.

Pressure-driven membrane processes are often classified by pore size into four categories: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Typical pressure ranges for these processes are given in Table 17.23. NF and RO primarily remove constituents through chemical diffusion.[83] MF and UF primarily remove constituents through physical sieving. An advantage of high-pressure processes is that they tend to remove a broader range of constituents than low-pressure processes. The drawback to broader removal is the increase in energy required for high-pressure processes.[83]

Electrical potential-driven membrane processes can also be used for arsenic removal. These processes include, for the purposes of this document, only electrodialysis reversal (EDR). In terms of achievable contaminant removal, EDR is comparable to RO. The separation process used in EDR, however, is ion exchange.

TABLE 17.23
Typical Pressure Ranges for Membrane Processes

Membrane Process	Pressure Range
MF	5–45 psi
UF	7–100 psi
NF	50–150 psi
RO	100–150 psi

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

17.11.2.4 Alternative Technologies

17.11.2.4.1 Iron Oxide Coated Sand

Iron oxide coated sand is a rare process that has shown some tendency for arsenic removal. Iron oxide coated sand consists of sand grains coated with ferric hydroxide that are used in fixed bed reactors to remove various dissolved metal species. The metal ions are exchanged with the surface hydroxides on the iron oxide coated sand. Iron oxide coated sand exhibits selectivity in the adsorption and exchange of ions present in the water. Like other processes, when the bed is exhausted it must be regenerated by a sequence of operations consisting of rinsing with regenerant, flushing with water, and neutralizing with strong acid. Sodium hydroxide is the most common regenerant, and sulfuric acid is the most common neutralizer.

Several studies have shown that iron oxide coated sand is effective for arsenic removal. Factors such as pH, arsenic oxidation state, competing ions, and regeneration have significant effects on the removes achieved with iron oxide coated sand.

17.11.2.4.2 Sulfur-Modified Iron

A patented sulfur-modified iron (SMI) process for arsenic removal has recently been developed.[84] The process consists of three components: (1) finely divided metallic iron, (2) powdered elemental sulfur or other sulfur compounds, and (3) an oxidizing agent. The powdered iron, powdered sulfur, and the oxidizing agent (H_20_2 in preliminary tests) are thoroughly mixed and then added to the water to be treated. The oxidizing agent serves to convert arsenite to arsenate. The solution is then mixed and settled.

Using the SMI process on several water types, high adsorptive capacities were obtained with final arsenic concentration of 0.050 mg/L. Arsenic removal was influenced by pH. Approximately 20-mg/L arsenic per gram of iron was removed at a pH of 8, and 50-mg arsenic per gram of iron was removed at a pH of 7. Arsenic removal seems to be very dependent on the iron to arsenic ratio.

Packed bed column tests demonstrated significant arsenic removal at residence times of 5 to 15 min. Significant removal of both arsenate and arsenite was measured. The highest adsorption capacity measured was 11-mg arsenic removed per gram of iron. Flow distribution problems were evident, as several columns became partially plugged and better arsenic removal was observed with reduced flow rates.

Spent media from the column tests were classified as nonhazardous waste. Projected operating costs for SMI when the process is operated below a pH of 8 are much lower than alternative arsenic removal technologies such as ferric chloride addition, reverse osmosis, and activated alumina. Cost savings would increase proportionally with increased flow rates and increased arsenic concentrations.

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Possible treatment systems using SMI include continuous stirred tank reactors, packed bed reactors, fluidized bed reactors, and passive *in situ* reactors. Packed bed and fluidized bed reactors appears to be the most promising for successful arsenic removal in pilot-scale and full-scale treatment systems based on present knowledge of the SMI process.

17.11.2.4.3 Granular Ferric Hydroxide

A new removal technique for arsenate that has recently been developed at the Technical University of Berlin (Germany) Department of Water Quality Control is adsorption on granular ferric hydroxide (GFH) in fixed bed reactors. This technique combines the advantages of the coagulation and filtration process, efficiency, and small residual mass with the fixed bed adsorption on activated alumina, and sample processing.

Driehaus et al. reported that the application of GFH in test adsorbers showed a high treatment capacity of 30,000 to 40,000 bed volumes with an effluent arsenate concentration never exceeding 10 μ/L. The typical residual mass was in the range of 5 to 25 g/m^3 treated water. The residue was a solid with an arsenate content of 1 to 10 g/kg. Table 17.24 summarizes the data of the adsorption tests.[85]

The competition of sulfate on arsenate adsorption was not very strong. Phosphate competed strongly with arsenate, which reduced arsenate removal with GFH. Arsenate adsorption decreases with pH, which is typical for anion adsorption. At high pH values GFH outperforms alumina. The performance is comparable at a pH below 7.6.

A field study reported by Simms et al. confirms the efficacy of GFH for arsenic removal.[86] Over the course of this study, a 5.3 MGD GHF located in the United Kingdom was found to reliably and consistently reduce average influent arsenic concentrations or 20 g/L to less than 10 g/L for 200,000 BV (over a year of operation) at an empty bed contact time of 3 min. Despite insignificant head loss, routine backwashing was conducted on a monthly basis to maintain media condition and to reduce the possibility of bacterial growth. The backwash was not hazardous and could be recycled or disposed to a sanitary sewer. At the time of replacement, arsenic loading on the media was 2.3%. Leachate tests conducted on the spent media found that arsenic did not leach from the media.

The most significant weakness of this technology appears to be its cost. Currently, GFH media costs approximately $4000/ ton. However, if a GFH bed can be used several times longer than an alumina bed, for example, it may prove to be the more cost-effective technology. Indeed, the system profiled in the field study presented above tested activated alumina as well as GFH. It found the GFH was sufficiently more efficient than smaller adsorption vessels and less media could be used to achieve the same level of arsenic removal (reducing costs). In addition, unlike activated alumina, GFH does not require preoxidation.

A treatment for leaching arsenic from the media to enable regeneration of GFH seems feasible, but it results in the generation of an alkaline solution with high levels of arsenate, requiring further treatment to obtain a solid waste. Direct disposal of spent GFH should be favored.

TABLE 17.24
Adsorption Tests on GFH

	Units	Test 1	Test 2	Test 3	Test 4
Raw Water Parameters					
pH	—	7.8	7.8	8.2	7.6
Arsenate concentration	μg/L	100–800	21	16	15–20
Phosphate concentration	μg/L	0.70	0.22	0.15	0.30
Conductivity	μsec/cm	780	480	200	460
Adsorption capacity for arsenate	g/kg	8.5	4.5	3.2	N/D[a]
Adsorber					
Bed height	m	0.24	0.16	0.15	0.82
Filter rate	m/h	6–10	7.6	5.7	15
Treatment capacity	BV	34,000	37,000	32,000	85,000
Maximum effluent concentration	μg/L	10	10	10	7
Arsenate content of GFH	g/kg	8.5	1.4	0.8	1.7
Mass of spent GFH (dry weight)	g/m^3	20.5	12	18	8.6

[a] N/D = not determined.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

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17.11.2.4.4 Iron Filings

Iron filings and sand may be used to reduce inorganic arsenic species to iron coprecipitates; mixed precipitates; and, in conjunction with sulfates, arsenopyrites. This type of process is essential to a filter technology, much like greensand filtration, wherein the source water is filtered through a bed of sand and iron filings. Unlike some technologies (e.g., ion exchange), sulfate is actually introduced in this process to encourage arsenopyrite precipitation.

This arsenic removal method was originally developed as a batch arsenic remediation technology. It appears to be quite effective in this use. Bench-scale tests indicate an average removal efficiency of 81% with much higher removals at lower influent concentrations. This method was tested to arsenic levels of 20,000 ppb, and at 2,000 ppb consistently reduced arsenic levels to less than 50 ppb (the current MCL). While it is quite effective in this capacity, its use as a drinking water treatment technology appears to be limited. In batch tests a residence time of approximately 7 d was required to reach the desired arsenic removal. In flowing conditions, even though removals averaged 81% and reached greater than 95% at 2000 ppb arsenic, there is no indication that this technology can reduce arsenic levels below approximately 25 ppb, there are no data to indicate how the technology can reduce arsenic levels below approximately 25 ppb, and there are no data to indicate how the technology performs at normal source water arsenic levels. This technology needs to be further evaluated before it can be recommended as an approved arsenic removal technology for drinking water.

17.11.2.4.5 Photo-Oxidation

Researchers at the Australian Nuclear Science and Technology Organization (ANSTO) have found that in the presence of light and naturally occurring light-absorbing materials, the oxidation rate of arsenite by oxygen can be increased ten-thousandfold.[87] The oxidized arsenic, now arsenate, can then be effectively removed by coprecipitation.

ANSTO evaluated both UV lamp reactors and sunlight-assisted-photo-oxidation using acidic, metal-bearing water from abandoned gold, silver, and lead mines. Air sparging was required for sunlight-assisted oxidation because of the high initial arsenate concentration (12 mg/L). Tests demonstrated that near complete oxidation of arsenite could be achieved using the photochemical process. In the analysis of process waters, 97% of the arsenic in the process stream was present as arsenate. Researchers also concluded that arsenite was preferentially oxidized in the presence of excess dissolved iron (22:1 iron to arsenic mole ratio). This is a contrast to conventional plants where dissolved iron represents an extra chemical oxidant demand that has to be satisfied during oxidation of arsenite.[87]

Photo-oxidation of the mine water followed by coprecipitation was able to reduce arsenic concentrations to as low as 17 g/L, which meets the current MCL for arsenic. Initial total arsenic concentrations were unknown, though the arsenite concentration was given as approximately 12 mg/L, which is considerably higher than typical raw water arsenic concentrations. ANSTO reported residuals from this process are environmentally stable and pass the Toxicity Characteristic Leaching Procedure test necessary to declare waste nonhazardous and suitable for landfill disposal.

Based on the removals achieved and residuals characteristics, it is expected that photo-oxidation followed by coprecipitation would be an effective arsenic removal technology. This technology is still largely experimental and should be further evaluated before recommendations as an approved arsenic removal technology for drinking water.

17.12 WHO IS ULTIMATELY RESPONSIBLE FOR DRINKING WATER QUALITY?

The SDWA gives EPA the responsibility for setting national drinking water standards that protect the health of the 250 million people who get their water from PWSs. Other people get their water from private wells that are not subject to federal regulations. Since 1974, EPA has set national standards for over 80 contaminants that may occur in drinking water.

While EPA and state governments set and enforce standards, local governments and private water suppliers have direct responsibility for the quality of the water that flows to the customer's tap. Water systems test and treat their water, maintain the distribution systems that deliver water to consumers, and report on their water quality to the state. States and EPA provide technical assistance to water suppliers and can take legal action against systems that fail to provide water that meets state and EPA standards.

As mentioned, EPA has set standards for more than 180 contaminants that may occur in drinking water and pose a risk to human health. EPA sets these standards to protect the health of everybody, including vulnerable groups like children. The contaminants fall into two groups according to the health effects that they cause. Local water suppliers normally alert customers through the local media, direct mail, or other means if there is a potential acute or chronic health effect from compounds in the drinking water. Customers may want to contact them for additional information specific to their area.

Acute effects occur within hours or days of the time that a person consumes a contaminant. People can suffer acute health effects from almost any contaminant if they are exposed to extraordinarily high levels (as in the case of a spill). In drinking water, microbes, such as bacteria and viruses, are the contaminants with the greatest chance of reaching levels high enough to cause acute health

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effects. Most people's bodies can fight off these microbial contaminants the way they fight off germs, and these acute contaminants typically do not have permanent effects. Nonetheless, when high enough levels occur, they can make people ill and can be dangerous or deadly for a person whose immune system is already weak due to HIV/AIDS, chemotherapy, steroid use, or another reason.

Chronic effects occur after people consume a contaminant at levels over EPA's safety standards for many years. The drinking water contaminants that can have chronic effects are chemicals (e.g., DBPs, solvents, and pesticides), radionuclides (e.g., radium), and minerals (e.g., arsenic). Examples of these chronic effects include cancer, liver or kidney problems, or reproductive difficulties.

17.13 CHAPTER REVIEW QUESTIONS AND PROBLEMS

17.1. What two minerals are primarily responsible for causing hard water?

17.2. The power of a substance to resist pH changes is referred to as a _____.

17.3. What chemical is used as a titrant when analyzing a water sample for carbon dioxide?

17.4. How many pounds of chlorine a day will be used if the dosage is 1.2 mg/L for a flow of 1,600,000 gal/d?

17.5. What is the specific capacity of a well having a yield of 60 gal/min with a drawdown of 25 ft?

17.6. What is the chlorine demand in milligrams per liter if the chlorine dosage is 1.0 mg/L and the residual chlorine is 0.5 mg/L?

17.7. If the chlorine dosage is 6 mg/L, what must the chlorine residual be if the chlorine demand is 3.3 mg/L?

17.8. A water treatment plant has a daily flow of 3.1 MGD. If the chlorinator setting is 220 lbs/day, and the chlorine demand is 6.9 mg/L, what is the chlorine residual?

17.9. A well log is best described as what?

17.10. The type of well construction not normally permitted for a public water supply is a _____.

17.11. Name three water quality tests routinely performed on water samples collected from storage tanks.

17.12. Paint for the interior of a drinking water storage tank must be approved by the _____.

17.13. Potable water is water that is _____.

17.14. A test of the effluent in the clear well shows that the required dosage of chlorine is 0.6 mg/L. The average daily flow at the treatment plant is 1 MGD. If we are using a hypochlorite solution with 68% available chlorine, how many pounds per day of hypochlorite will be required?

17.15. A waterworks conveys piped water to the _____.

17.16. What does the hydrologic cycle describe?

17.17. Is *Giardia lamblia* a chronic or acute health threat?

17.18. Define disinfection.

17.19. As disinfectants _____ are as common as household bleach.

17.20. What must effective disinfectants do?

17.21. How many pounds of chlorine will be used if the dosage is 0.4 mg/L for a flow of 5,300,000 gal/d?

17.22. If the chlorine dosage is 10 mg/L, what must the chlorine residual be if the demand is 2.6 mg/L?

17.23. There are a number of possible interferences with chlorine disinfection. Name one.

17.24. If a dose of soda ash is 0.8 mg/L for a flow of 2.6 MGD, find the rate of soda ash in pounds per day.

17.25. A circular clarifier handles a flow of 0.75 MGD. The clarifier has a 20-ft radius and a depth of 10 ft. Find the detention time.

17.26. A water treatment plant operates at a rate of 2 MGD. The dosage of alum is 35 ppm (or mg/L). How many pounds of alum are used per day?

17.27. True or false: By weight, more pounds (65%) of HTH than pounds of chlorine are needed to get the same number of pounds of available chlorine into the water.

17.28. _____ is the amount of chlorine present in water after a specified time period.

17.29. For a potable water system to be contaminated by water from a nonpotable system through a cross-connection, two conditions must exist simultaneously. What are they?

17.30. A piping arrangement that could allow a nontoxic substance, such as milk, beer, or orange juice, to contaminate a potable water system would be classified as a _____ hazard situation.

17.31. When firefighting, main breaks or heavy water usage withdraws more water from a potable water system than is being supplied to the system. As a result, _____ or _____ pressure may develop in the potable system.

17.32. What type of pump uses roller and tubing?

17.33. List three watershed management practices.

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17.34. A filter plant has 3 filters, each measuring 10×7 ft. One filter is out of service, and the other filters together are capable of filtering 280 gal/min. How many gallons per square foot per minute will each filter?

17.35. A filter having an area of 300 ft^2 is ready to be backwashed. Assume a rate of 15 gal/ft^2/min and 8 min. of backwash is required. What is the amount of water in gallons required for each backwash?

17.36. If water travels 600 ft in five minutes, what is the velocity?

17.37. Where should you look to find information about the hazards associated with the various chemicals you come into contact with at your treatment plant?

17.38. What two water unit treatment processes have done the most to eradicate or reduce the level of waterborne disease in the U.S.?

17.39. If the discharge pressure is lower than the pump is rated for, what will the pump do?

17.40. The most effective chlorine compound for killing or inactivating pathogens is _____.

17.41. The group of microorganisms that forms cysts and thus becomes resistant to disinfection is _____.

17.42. SWTR contains operational and monitoring requirements to ensure what?

17.43. The aggressive index is in indicator of _____.

17.44. List three factors that influence coagulant dose.

17.45. Flow is a 2.5-ft wide rectangular channel is 1.4-ft deep and measures 11.2 ft^3/sec. What is the average velocity?

17.46. A cylindrical tank is 100 ft high and 20 ft in diameter. How many gallons of water will it contain?

17.47. What is the correct sequence for running a jar test?

17.48. The purpose of coagulation and flocculation is to accomplish what function?

17.49. What is the goal of chemical precipitation?

17.50. To achieve optimum removal of hardness, one should add how much lime and soda ash?

17.51. What percentage of positive samples cannot be exceeded for bacteriological compliance monitoring of a distribution system?

17.52. What is the velocity in feet per minute if water travels 1500 ft in 4 min? What is the velocity in feet per second?

17.53. A type of valve in a water distribution system used to isolate a damaged line would be a _____ valve.

17.54. Under the Lead and Copper Rule what must a treatment facility do?

17.55. Fluoridation at 0.2 mg/L below optimum cuts effectiveness by what percentage?

17.56. The chemical normally used in a fluoride saturator is _____.

17.57. Long-term consumption of water with a fluoride concentration of 3.0 mg/L or more may cause _____.

17.58. If a raw water source has a fluoride ion concentration of 0.15 mg/L and the optimum concentration for the fluoride ion is 0.9 mg/L, what is the desired fluoride dose?

17.59. What does the jar test in water treatment determine?

17.60. Inorganic phosphate addition normally functions to work as _____.

17.61. The flow in a 6-in. pipe is 350 gal/min. What is the average velocity?

17.62. What is used to oxidize iron and manganese?

17.63. List three factors that affect corrosion.

17.64. Activated carbon removes taste and odor producing substances by what method?

17.65. To achieve good coagulation in low alkalinity waters, an additional source of alkalinity is most effective when added at what point?

17.66. To prevent media loss, when should supplemental backwash air flow and surface sweeps be turned off?

17.67. The most common complaint concerning taste and odor primarily involves _____.

17.68. True or false: The concentration of volatile organic compounds (VOCs) is usually greater in groundwater.

17.69. True or false: VOCs are suspected of being potential carcinogens.

17.70. List three ways in which to remove VOCs from water.

17.71. A round tank 30-ft in diameter is filled with water to a depth of 15 ft. How many gallons of water are in the tank?

17.72. What chemical substance is used to reduce trihalomethane formation?

17.73. What causes brownish-blackish waters?

17.74. Waters that cause bluish-green stains on household fixtures often contain _____.

17.75. What causes water hardness?

17.76. When Fe+2 is chemically changed to Fe+3, what happens to the iron atom?

17.77. Alkalinity is caused by a _____.

17.78. If the head loss, in feet, at any level in the filter bed exceeds the depth of the water above the same point (static head), a vacuum can result. This situation is referred to as _____.

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17.79. Sedimentation is the removal of settleable solids by _____.

17.80. In sedimentation, the _____ zone decreases the velocity of the incoming water and distributes the flow evenly across the basin.

17.81. As water enters a sedimentation basin, _____ flow distribution is important to achieve proper velocity throughout the basin.

17.82. List the three purposes of enhanced coagulation.

17.83. For a water plant that performs bacteriological analysis, what is the maximum hold time from when the sample is collected until analysis is started in the lab?

17.84. When performing a chlorine residual test with an amperometric titrator, what reagent is used as the titrant?

17.85. How many gallons of water fell into a 20-acre reservoir if the water level of the pond rose 2 in. after a storm event?

17.86. To maintain a 0.5 mg/L chlorine residual throughout the distribution system, a chlorine dosage of 1.2 mg/L is required at the clear well. If the average daily flow reaches 2.0 MGD, how many pounds per day of chlorine must be added?

17.87. A cylindrical water storage tank is 70 ft tall and 30 ft in diameter. The tank is 40% full. What is the water pressure in pounds per square inch at the base of the tank?

17.88. The concentration of VOCs is usually greater in _____.

17.89. List three methods to remove VOCs.

17.90. The addition of _____ is a method to reduce THM formation.

17.91. The ability of soil to allow water to pass through it is called its _____.

17.92. The top of an aquifer is called the _____.

17.93. Diseases that are carried by water are referred to as _____ diseases.

17.94. A chemical that combines with suspended particles in water is called a _____.

17.95. When water freezes, its volume becomes _____.

17.96. The most commonly used algicide is _____.

17.97. Carbonate hardness can be removed by adding _____ to the water.

17.98. To remove coliforms and pathogens, water must be _____.

17.99. Biochemical oxygen demand helps the plant operator determine how much _____ will be needed to stabilize the organic matter.

. 17.100. Bacteria are produced by dividing in half, which is called _____.

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18 Wastewater Treatment

According to the Code of Federal Regulations (CFR) 40 CFR Part 403, regulations were established in the late 1970s and early 1980s to help publicly owned treatment works (POTW) control industrial discharges to sewers. These regulations were designed to prevent pass-through and interference at the treatment plants and interference in the collection and transmission systems.

Pass-through occurs when pollutants literally pass through a POTW without being properly treated, and cause the POTW to have an effluent violation or increase the magnitude or duration of a violation.

Interference occurs when a pollutant discharge causes a POTW to violate its permit by inhibiting or disrupting treatment processes, treatment operations, or processes related to sludge use or disposal.

18.1 WASTEWATER OPERATORS

Like waterworks operators, wastewater operators are highly trained and artful practitioners and technicians of their trade. Both operators are also required by the states to be licensed or certified to operate a wastewater treatment plant.

When learning wastewater operator skills, there are a number of excellent texts available to aid in the training process. Many of these texts are listed in Table 18.1.

18.1.1 The Wastewater Treatment Process: The Model

Figure 18.1 shows a basic schematic of an example wastewater treatment process providing primary and secondary treatment using the activated sludge process. This is the model, prototype, and paradigm used in this book. Though it is true that in secondary treatment (which provides biochemical oxygen demand [BOD] removal beyond what is achievable by simple sedimentation), there are actually three commonly used approaches (trickling filter, activated sludge, and oxidation ponds). For instructive and illustrative purposes, we focus on the activated sludge process throughout this handbook. The purpose of Figure 18.1 is to allow the reader to follow the treatment process step-by-step as it is presented (and as it is actually configured in the real world) and to assist understanding of how all the various unit processes sequentially follow and tie into each other.

We begin certain sections (which discuss unit processes) with frequent reference to Figure 18.1. It is important to begin these sections in this manner because wastewater treatment is a series of individual steps (unit processes) that treat the wastestream as it makes its way through the entire process. It logically follows that a pictorial presentation along with pertinent written information enhances the learning process. It should also be pointed out that even though the model shown in Figure 18.1 does not include all unit processes currently used in wastewater treatment, we do not ignore the other major processes: trickling filters, rotating biological contactors (RBCs), and oxidation ponds.

18.2 WASTEWATER TERMINOLOGY AND DEFINITIONS

Wastewater treatment technology, like many other technical fields, has its own unique terms with their own meaning. Though some of the terms are unique, many are common to other professions. Remember that the science of wastewater treatment is a combination of engineering, biology, mathematics, hydrology, chemistry, physics, and other disciplines. Many of the terms used in engineering, biology, mathematics, hydrology, chemistry, physics, and others are also used in wastewater treatment. Those terms not listed or defined in the following section will be defined as they appear in the text.

18.2.1 Terminology and Definitions

Activated sludge the solids formed when microorganisms are used to treat wastewater using the activated sludge treatment process. It includes organisms, accumulated food materials, and waste products from the aerobic decomposition process.

Advanced waste treatment treatment technology used to produce an extremely high quality discharge.

Aerobic conditions in which free, elemental oxygen is present. Also used to describe organisms, biological activity, or treatment processes that require free oxygen.

Anaerobic conditions in which no oxygen (free or combined) is available. Also used to describe organisms, biological activity or treatment processes that function in the absence of oxygen.

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TABLE 18.1
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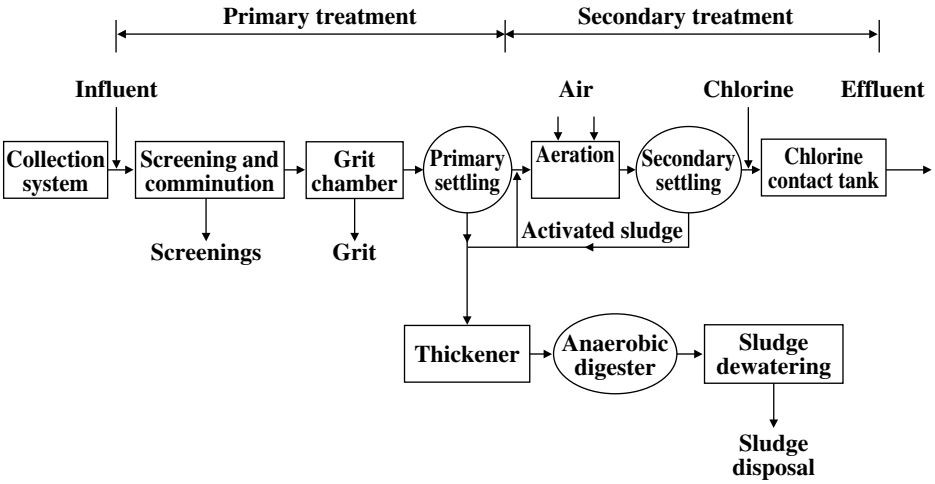

FIGURE 18.1 Schematic of an example wastewater treatment process providing primary and secondary treatment using activated sludge process. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Anoxic conditions in which no free, elemental oxygen is present. The only source of oxygen is combined oxygen, such as that found in nitrate compounds. Also used to describe biological activity of treatment processes that function only in the presence of combined oxygen.

Average monthly discharge limitation the highest allowable discharge over a calendar month.

Average weekly discharge limitation the highest allowable discharge over a calendar week.

Biochemical oxygen demand (BOD) the amount of organic matter that can be biologically oxidized under controlled conditions (5 days @ 20°C in the dark).

Biosolids (from 1977) solid organic matter recovered from a sewage treatment process and used especially as fertilizer (or soil amendment); usually used in plural (from *Merriam-Webster's Collegiate Dictionary, 10th ed.*, 1998).

Note: In this text, biosolids is used in many places (activated sludge being the exception) to replace the standard term sludge. The author views the term sludge as an ugly, inappropriate four-letter word to describe biosolids. Biosolids

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is a product that can be reused; it has some value. Because biosolids has value, it certainly should not be classified as a waste product, and when biosolids for beneficial reuse is addressed, it is made clear that it is not.

Buffer a substance or solution which resists changes in pH.

Carbonaceous biochemical oxygen demand ($CBOD_5$) the amount of biochemical oxygen demand that can be attributed to carbonaceous material.

Chemical oxygen demand (COD) the amount of chemically oxidizable materials present in the wastewater.

Clarifier a device designed to permit solids to settle or rise and be separated from the flow. Also known as a settling tank or sedimentation basin.

Coliform a type of bacteria used to indicate possible human or animal contamination of water.

Combined sewer a collection system that carries both wastewater and storm water flows.

Comminution a process that shreds solids into smaller, less harmful particles.

Composite sample a combination of individual samples taken in proportion to flow.

Daily discharge the discharge of a pollutant measured during a calendar day or any 24-h period that reasonably represents a calendar day for the purposes of sampling. Limitations expressed as weight is total mass (weight) discharged over the day. Limitations expressed in other units are average measurements of the day.

Daily maximum discharge the highest allowable values for a daily discharge.

Detention time the theoretical time water remains in a tank at a given flow rate.

Dewatering the removal or separation of a portion of water present in a sludge or slurry.

Discharge monitoring report (DMR) the monthly report required by the treatment plant's National Pollutant Discharge Elimination System (NPDES) discharge permit.

Dissolved oxygen (DO) free or elemental oxygen that is dissolved in water.

Effluent the flow leaving a tank, channel, or treatment process.

Effluent limitation any restriction imposed by the regulatory agency on quantities, discharge rates, or concentrations of pollutants that are discharged from point sources into state waters.

Facultative organisms that can survive and function in the presence or absence of free, elemental oxygen.

Fecal coliform a type of bacteria found in the bodily discharges of warm-blooded animals. Used as an indicator organism.

Floc solids which join together to form larger particles which will settle better.

Flume a flow rate measurement device.

Food-to-microorganism ratio (F:M) an activated sludge process control calculation based upon the amount of food (BOD or COD) available per pound of mixed liquor volatile suspended solids.

Grab sample an individual sample collected at a randomly selected time.

Grit heavy inorganic solids such as sand, gravel, egg shells, or metal filings.

Industrial wastewater wastes associated with industrial manufacturing processes.

Infiltration/inflow extraneous flows in sewers; simply, inflow is water discharged into sewer pipes or service connections from such sources as foundation drains, roof leaders, cellar and yard area drains, cooling water from air conditioners, and other clean-water discharges from commercial and industrial establishments. Defined by Metcalf & Eddy as follows:[1]

- **Infiltration** water entering the collection system through cracks, joints, or breaks.
- **Steady inflow** water discharged from cellar and foundation drains, cooling water discharges, and drains from springs and swampy areas. This type of inflow is steady and is identified and measured along with infiltration.
- **Direct flow** those types of inflow that have a direct stormwater runoff connection to the sanitary sewer and cause an almost immediate increase in wastewater flows. Possible sources are roof leaders, yard and areaway drains, manhole covers, cross connections from storm drains and catch basins, and combined sewers.
- **Total inflow** the sum of the direct inflow at any point in the system plus any flow discharged from the system upstream through overflows, pumping station bypasses, and the like.
- **Delayed inflow** stormwater that may require several days or more to drain through the sewer system. This category can include the discharge of sump pumps from cellar drainage as well as the slowed entry of surface water through manholes in ponded areas.

Influent the wastewater entering a tank, channel, or treatment process.

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Inorganic mineral materials such as salt, ferric chloride, iron, sand, gravel, etc.

License a certificate issued by the state board of waterworks or wastewater works operators authorizing the holder to perform the duties of a wastewater treatment plant operator.

Mean cell residence time (MCRT) the average length of time a mixed liquor suspended solids particle remains in the activated sludge process. May also be known as sludge retention time.

Mixed liquor the combination of return activated sludge and wastewater in the aeration tank.

Mixed liquor suspended solids (MLSS) the suspended solids concentration of the mixed liquor.

Mixed liquor volatile suspended solids (MLVSS) the concentration of organic matter in the mixed liquor suspended solids.

Milligrams/Liter (mg/L) a measure of concentration. It is equivalent to parts per million.

National Pollutant Discharge Elimination System permit permit that authorizes the discharge of treated wastes and specifies the condition, which must be met for discharge.

Nitrogenous oxygen demand (NOD) a measure of the amount of oxygen required to biologically oxidize nitrogen compounds under specified conditions of time and temperature.

Nutrients substances required to support living organisms. Usually refers to nitrogen, phosphorus, iron, and other trace metals.

Organic materials that consist of carbon, hydrogen, oxygen, sulfur, and nitrogen. Many organics are biologically degradable. All organic compounds can be converted to carbon dioxide and water when subjected to high temperatures.

Pathogenic disease causing. A pathogenic organism is capable of causing illness.

Point source any discernible, defined, and discrete conveyance from which pollutants are or may be discharged.

Part per million (ppm) an alternative (but numerically equivalent) unit used in chemistry is milligrams per liter. As an analogy, think of this unit as being equivalent to a full shot glass in a swimming pool.

Return activated sludge solids (RASS) the concentration of suspended solids in the sludge flow being returned from the settling tank to the head of the aeration tank.

Sanitary wastewater wastes discharged from residences and from commercial, institutional, and similar facilities that include both sewage and industrial wastes.

Scum the mixture of floatable solids and water that is removed from the surface of the settling tank.

Septic a wastewater that has no dissolved oxygen present. Generally characterized by black color and rotten egg (hydrogen sulfide) odors.

Settleability a process control test used to evaluate the settling characteristics of the activated sludge. Readings taken at 30 to 60 min are used to calculate the settled sludge volume and the sludge volume index.

Settled sludge volume (SSV) the volume in percent occupied by an activated sludge sample after 30 to 60 minutes of settling. Normally written as SSV with a subscript to indicate the time of the reading used for calculation (SSV_{60}) or (SSV_{30}).

Sewage wastewater containing human wastes.

Sludge the mixture of settleable solids and water that is removed from the bottom of the settling tank.

Sludge retention time (SRT) see mean cell residence time.

Sludge volume index (SVI) a process control calculation that is used to evaluate the settling quality of the activated sludge. Requires the SSV_{30} and mixed liquor suspended solids test results to calculate.

Storm sewer a collection system designed to carry only storm water runoff.

Storm water runoff resulting from rainfall and snowmelt.

Supernatant the amber-colored liquid above the sludge that is in a digester.

Wastewater the water supply of the community after it has been soiled by use.

Waste activated sludge solids (WASS) the concentration of suspended solids in the sludge, which is being removed from the activated sludge process.

Weir a device used to measure wastewater flow.

Zoogleal slime the biological slime which forms on fixed film treatment devices. It contains a wide variety of organisms essential to the treatment process.

18.3 MEASURING PLANT PERFORMANCE

To evaluate how well a plant or treatment unit process is operating, performance efficiency or percent removal is used. The results can be compared with those listed in the plant's operation and maintenance manual (O & M) to determine if the facility is performing as expected. In this chapter sample calculations often used to measure plant performance and efficiency are presented.

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18.3.1 Plant Performance and Efficiency

Note: The calculation used for determining the performance (percent removal) for a digester is different from that used for performance (percent removal) for other processes. Care must be taken to select the right formula

The following equation is used to determine plant performance and efficiency:

$$\% \text{ Removal} = \frac{[\text{Influent Concentration} - \text{Effluent Concentration}] \times 100}{\text{Influent Concentration}} \quad (18.1)$$

Example 18.1

Problem:

The influent BOD is 247 mg/L and the plant effluent BOD is 17 mg/L. What is the percent removal?

Solution:

$$\% \text{ Removal} = \frac{[247 \text{ mg/L} - 17 \text{ mg/L}] \times 100}{247 \text{ mg/L}}$$

$$= 93\%$$

18.3.2 Unit Process Performance and Efficiency

Equation 18.1 is used again to determine unit process efficiency. The concentration entering the unit and the concentration leaving the unit (i.e., primary, secondary, etc.) are used to determine the unit performance.

Example 18.2

Problem:

The primary influent BOD is 235 mg/L and the primary effluent BOD is 169 mg/L. What is the percent removal?

$$\% \text{ Removal} = \frac{[235 \text{ mg/L} - 169 \text{ mg/L}] \times 100}{235 \text{ mg/L}}$$

$$= 28\%$$

18.3.3 Percent Volatile Matter Reduction in Sludge

The calculation used to determine percent volatile matter (%VM) reduction is more complicated because of the changes occurring during sludge digestion:

$$\%\text{VM Reduction} = \frac{[\%\text{VM}_{in} - \%\text{VM}_{out}] \times 100}{[\%\text{VM}_{in} - (\%\text{VM}_{in} \times \%\text{VM}_{out})]} \quad (18.2)$$

Example 18.3

Problem:

Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Data:

Raw sludge volatile matter = 74%
Digested sludge volatile matter = 54%

$$\%\text{VM Reduction} = \frac{[0.74 - 0.54] \times 100}{[0.74 - (0.74 \times 0.54)]}$$

$$= 59\%$$

18.4 HYDRAULIC DETENTION TIME

The term detention time (DT) or hydraulic detention time (HDT) refers to the average length of time (theoretical time) a drop of water, wastewater, or suspended particles remains in a tank or channel. It is calculated by dividing the water or wastewater in the tank by the flow rate through the tank. The units of flow rate used in the calculation are dependent on whether the detention time is to be calculated in seconds, minutes, hours or days. Detention time is used in conjunction with various treatment processes, including sedimentation and coagulation and flocculation.

Generally, in practice, detention time is associated with the amount of time required for a tank to empty. The range of detention time varies with the process. For example, in a tank used for sedimentation, detention time is commonly measured in minutes.

The calculation methods used to determine detention time are illustrated in the following sections.

18.4.1 Detention Time in Days

Use Equation 18.3 to calculate the detention time in days:

$$\text{HDT (d)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3}{\text{Q (gal/d)}} \quad (18.3)$$

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Example 18.4

Problem:

An anaerobic digester has a volume of 2,400,000 gal. What is the detention time in days when the influent flow rate is 0.07 MGD?

Solution:

$$\text{DT (d)} = \frac{2{,}400{,}000 \text{ gal}}{0.07 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}$$

$$= 34 \text{ d}$$

18.4.2 Detention Time in Hours

$$\text{HDT (h)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3 \times 24 \text{ h/d}}{\text{Q (gal/d)}} \quad (18.4)$$

Example 18.5

Problem:

A settling tank has a volume of 44,000 ft.^{3} What is the detention time in hours when the flow is 4.15 MGD?

$$\text{DT (h)} = \frac{44{,}000 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 24 \text{ h/d}}{4.15 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}$$

$$= 1.9 \text{ h}$$

18.4.3 Detention Time in Minutes

$$\text{HDT (min)} = \frac{\text{Tank Volume } (\text{ft}^3) \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/d}}{\text{Q (gal/d)}} \quad (18.5)$$

Example 18.6

Problem:

A grit channel has a volume of 1340 ft.^{3} What is the detention time in minutes when the flow rate is 4.3 MGD?

Solution:

$$\text{DT (min)} = \frac{1340 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 \times 1440 \text{ min/d}}{4{,}300{,}000 \text{ gal/d}}$$

$$= 3.36 \text{ min}$$

Note: The tank volume and the flow rate must be in the same dimensions before calculating the hydraulic detention time.

18.5 WASTEWATER SOURCES AND CHARACTERISTICS

Wastewater treatment is designed to use the natural purification processes (self-purification processes of streams and rivers) to the maximum level possible. It is also designed to complete these processes in a controlled environment rather than over many miles of a stream or river. Moreover, the treatment plant is also designed to remove other contaminants that are not normally subjected to natural processes, as well as treating the solids that are generated through the treatment unit steps. The typical wastewater treatment plant is designed to achieve many different purposes:

1. Protect public health.
2. Protect public water supplies.
3. Protect aquatic life.
4. Preserve the best uses of the waters.
5. Protect adjacent lands.

Wastewater treatment is a series of steps. Each of the steps can be accomplished using one or more treatment processes or types of equipment. The major categories of treatment steps are:

1. Preliminary treatment — Removes materials that could damage plant equipment or would occupy treatment capacity without being treated.
2. Primary treatment — Removes settleable and floatable solids (may not be present in all treatment plants).
3. Secondary treatment — Removes BOD and dissolved and colloidal suspended organic matter by biological action. Organics are converted to stable solids, carbon dioxide and more organisms.
4. Advanced waste treatment — Uses physical, chemical, and biological processes to remove additional BOD, solids and nutrients (not present in all treatment plants).
5. Disinfection — Removes microorganisms to eliminate or reduce the possibility of disease when the flow is discharged.
6. Sludge treatment — Stabilizes the solids removed from wastewater during treatment, inactivates pathogenic organisms, and reduces the volume of the sludge by removing water.

The various treatment processes described above are discussed in detail later.

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18.5.1 Wastewater Sources

The principal sources of domestic wastewater in a community are the residential areas and commercial districts. Other important sources include institutional and recreational facilities and storm water (runoff) and groundwater (infiltration). Each source produces wastewater with specific characteristics. In this section wastewater sources and the specific characteristics of wastewater are described.

18.5.1.1 Generation of Wastewater

Wastewater is generated by five major sources: human and animal wastes, household wastes, industrial wastes, storm water runoff, and groundwater infiltration.

1. Human and animal wastes — Contains the solid and liquid discharges of humans and animals and is considered by many to be the most dangerous from a human health viewpoint. The primary health hazard is presented by the millions of bacteria, viruses, and other microorganisms (some of which may be pathogenic) present in the wastestream.
2. Household wastes — Consists of wastes, other than human and animal wastes, discharged from the home. Household wastes usually contain paper, household cleaners, detergents, trash, garbage, and other substances the homeowner discharges into the sewer system.
3. Industrial wastes — Includes industry specific materials that can be discharged from industrial processes into the collection system. Typically contains chemicals, dyes, acids, alkalis, grit, detergents, and highly toxic materials.
4. Storm water runoff — Many collection systems are designed to carry both the wastes of the community and storm water runoff. In this type of system when a storm event occurs, the wastestream can contain large amounts of sand, gravel, and other grit as well as excessive amounts of water.
5. Groundwater infiltration — Groundwater will enter older improperly sealed collection systems through cracks or unsealed pipe joints. Not only can this add large amounts of water to wastewater flows, but also additional grit.

18.5.2 Classification of Wastewater

Wastewater can be classified according to the sources of flows: domestic, sanitary, industrial, combined, and storm water.

1. Domestic (sewage) wastewater — Contains mainly human and animal wastes, household wastes, small amounts of groundwater infiltration and small amounts of industrial wastes.
2. Sanitary wastewater — Consists of domestic wastes and significant amounts of industrial wastes. In many cases, the industrial wastes can be treated without special precautions. However, in some cases, the industrial wastes will require special precautions or a pretreatment program to ensure the wastes do not cause compliance problems for the wastewater treatment plant.
3. Industrial wastewater — Consists of industrial wastes only. Often the industry will determine that it is safer and more economical to treat its waste independent of domestic waste.
4. Combined wastewater — Consists of a combination of sanitary wastewater and storm water runoff. All the wastewater and storm water of the community is transported through one system to the treatment plant.
5. Storm water — Contains a separate collection system (no sanitary waste) that carries storm water runoff including street debris, road salt, and grit.

18.5.3 Wastewater Characteristics

Wastewater contains many different substances that can be used to characterize it. The specific substances and amounts or concentrations of each will vary, depending on the source. It is difficult to precisely characterize wastewater. Instead, wastewater characterization is usually based on and applied to an average domestic wastewater.

Note: Keep in mind that other sources and types of wastewater can dramatically change the characteristics.

Wastewater is characterized in terms of its physical, chemical, and biological characteristics.

18.5.3.1 Physical Characteristics

The physical characteristics of wastewater are based on color, odor, temperature, and flow.

1. Color — Fresh wastewater is usually a light brownish-gray color. However, typical wastewater is gray and has a cloudy appearance. The color of the wastewater will change significantly if allowed to go septic (if travel time in the collection system increases). Typical septic wastewater will have a black color.
2. Odor — Odors in domestic wastewater usually are caused by gases produced by the decomposition of organic matter or by other substances

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added to the wastewater. Fresh domestic wastewater has a musty odor. If the wastewater is allowed to go septic, this odor will significantly change to a rotten egg odor associated with the production of hydrogen sulfide (H_2S).

3. Temperature — the temperature of wastewater is commonly higher than that of the water supply because of the addition of warm water from households and industrial plants. However, significant amounts of infiltration or storm water flow can cause major temperature fluctuations.
4. Flow — the actual volume of wastewater is commonly used as a physical characterization of wastewater and is normally expressed in terms of gallons per person per day. Most treatment plants are designed using an expected flow of 100 to 200 gallons per person per day. This figure may have to be revised to reflect the degree of infiltration or storm flow the plant receives. Flow rates will vary throughout the day. This variation, which can be as much as 50 to 200% of the average daily flow is known as the diurnal flow variation.

Note: Diurnal means occurring in a day or daily.

18.5.3.2 Chemical Characteristics

In describing the chemical characteristics of wastewater, the discussion generally includes topics such as organic matter, the measurement of organic matter, inorganic matter, and gases. For the sake of simplicity, in this handbook we specifically describe chemical characteristics in terms of alkalinity, BOD, chemical oxygen demand (COD), dissolved gases, nitrogen compounds, pH, phosphorus, solids (organic, inorganic, suspended, and dissolved solids), and water.

1. Alkalinity — This is a measure of the wastewater's capability to neutralize acids. It is measured in terms of bicarbonate, carbonate, and hydroxide alkalinity. Alkalinity is essential to buffer (hold the neutral pH) of the wastewater during the biological treatment processes.
2. Biochemical oxygen demand — This is a measure of the amount of biodegradable matter in the wastewater. Normally measured by a 5-d test conducted at 20°C. The BOD_5 domestic waste is normally in the range of 100 to 300 mg/L.
3. Chemical oxygen demand — This is a measure of the amount of oxidizable matter present in the sample. The COD is normally in the range of 200 to 500 mg/L. The presence of industrial wastes can increase this significantly.
4. Dissolved gases — These are gases that are dissolved in wastewater. The specific gases and normal concentrations are based upon the composition of the wastewater. Typical domestic wastewater contains oxygen in relatively low concentrations, carbon dioxide, and hydrogen sulfide (if septic conditions exist).
5. Nitrogen compounds — The type and amount of nitrogen present will vary from the raw wastewater to the treated effluent. Nitrogen follows a cycle of oxidation and reduction. Most of the nitrogen in untreated wastewater will be in the forms of organic nitrogen and ammonia nitrogen. Laboratory tests exist for determination of both of these forms. The sum of these two forms of nitrogen is also measured and is known as total kjeldahl nitrogen (TKN). Wastewater will normally contain between 20 to 85 mg/L of nitrogen. Organic nitrogen will normally be in the range of 8 to 35 mg/L, and ammonia nitrogen will be in the range of 12 to 50 mg/L.
6. pH — This is a method of expressing the acid condition of the wastewater. pH is expressed on a scale of 1 to 14. For proper treatment, wastewater pH should normally be in the range of 6.5 to 9.0 (ideally 6.5 to 8.0).
7. Phosphorus — This element is essential to biological activity and must be present in at least minimum quantities or secondary treatment processes will not perform. Excessive amounts can cause stream damage and excessive algal growth. Phosphorus will normally be in the range of 6 to 20 mg/L. The removal of phosphate compounds from detergents has had a significant impact on the amounts of phosphorus in wastewater.
8. Solids — Most pollutants found in wastewater can be classified as solids. Wastewater treatment is generally designed to remove solids or to convert solids to a form that is more stable or can be removed. Solids can be classified by their chemical composition (organic or inorganic) or by their physical characteristics (settleable, floatable, and colloidal). Concentration of total solids in wastewater is normally in the range of 350 to 1200 mg/L.
   A. Organic solids — Consists of carbon, hydrogen, oxygen, nitrogen and can be converted to carbon dioxide and water by ignition at 550°C. Also known as fixed solids or loss on ignition.
   B. Inorganic solids — Mineral solids that are unaffected by ignition. Also known as fixed solids or ash.

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C. Suspended solids — These solids will not pass through a glass fiber filter pad. Can be further classified as Total suspended solids (TSS), volatile suspended solids, and fixed suspended solids. Can also be separated into three components based on settling characteristics: settleable solids, floatable solids, and colloidal solids. Total suspended solids in wastewater are normally in the range of 100 to 350 mg/L.

D. Dissolved solids — These solids will pass through a glass fiber filter pad. Can also be classified as total dissolved solids (TDS), volatile dissolved solids, and fixed dissolved solids. TDS are normally in the range of 250 to 850 mg/L.

9. Water — This is always the major constituent of wastewater. In most cases water makes up 99.5 to 99.9% of the wastewater. Even in the strongest wastewater, the total amount of contamination present is less than 0.5% of the total and in average strength wastes it is usually less than 0.1%.

18.5.3.3 Biological Characteristics and Processes

(Note: The biological characteristics of water were discussed in detail earlier in this text.)

After undergoing physical aspects of treatment (i.e., screening, grit removal, and sedimentation) in preliminary and primary treatment, wastewater still contains some suspended solids and other solids that are dissolved in the water. In a natural stream, such substances are a source of food for protozoa, fungi, algae, and several varieties of bacteria. In secondary wastewater treatment, these same microscopic organisms (which are one of the main reasons for treating wastewater) are allowed to work as fast as they can to biologically convert the dissolved solids to suspended solids that will physically settle out at the end of secondary treatment.

Raw wastewater influent typically contains millions of organisms. The majority of these organisms are nonpathogenic, but several pathogenic organisms may also be present. (These may include the organisms responsible for diseases such as typhoid, tetanus, hepatitis, dysentery, gastroenteritis, and others.)

Many of the organisms found in wastewater are microscopic (microorganisms); they include algae, bacteria, protozoa (e.g., amoeba, flagellates, free-swimming ciliates, and stalked ciliates), rotifers, and viruses.

Table 18.2 is a summary of typical domestic wastewater characteristics.

TABLE 18.2
Typical Domestic Wastewater Characteristics

Characteristic	Typical Characteristic
Color	Gray
Odor	Musty
DO	>1.0 mg/L
pH	6.5–9.0
TSS	100–350 mg/L
BOD	100–300 mg/L
COD	200–500 mg/L
Flow	100–200 gal/person/d
Total nitrogen	20–85 mg/L
Total phosphorus	6–20 mg/L
Fecal coliform	500,000–3,000,000 MPN/100 mL

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

18.6 WASTEWATER COLLECTION SYSTEMS

Wastewater collection systems collect and convey wastewater to the treatment plant. The complexity of the system depends on the size of the community and the type of system selected. Methods of collection and conveyance of wastewater include gravity systems, force main systems, vacuum systems, and combinations of all three types of systems.

18.6.1 Gravity Collection System

In a gravity collection system, the collection lines are sloped to permit the flow to move through the system with as little pumping as possible. The slope of the lines must keep the wastewater moving at a velocity (speed) of 2 to 4 ft/sec. Otherwise, at lower velocities, solids will settle out and cause clogged lines, overflows, and offensive odors. To keep collection systems lines at a reasonable depth, wastewater must be lifted (pumped) periodically so that it can continue flowing downhill to the treatment plant. Pump stations are installed at selected points within the system for this purpose.

18.6.2 Force Main Collection System

In a typical force main collection system, wastewater is collected to central points and pumped under pressure to the treatment plant. The system is normally used for conveying wastewater long distances. The use of the force main system allows the wastewater to flow to the treatment plant at the desired velocity without using sloped lines. It should be noted that the pump station discharge lines in a gravity system are considered to be force mains since the content of the lines is under pressure.

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Note: Extra care must be taken when performing maintenance on force main systems since the content of the collection system is under pressure.

18.6.3 Vacuum System

In a vacuum collection system, wastewaters are collected to central points and then drawn toward the treatment plant under vacuum. The system consists of a large amount of mechanical equipment and requires a large amount of maintenance to perform properly. Generally, the vacuum-type collection systems are not economically feasible.

18.6.4 Pumping Stations

Pumping stations provide the motive force (energy) to keep the wastewater moving at the desired velocity. They are used in both the force main and gravity systems. They are designed in several different configurations and may use different sources of energy to move the wastewater (i.e., pumps, air pressure or vacuum). One of the more commonly used types of pumping station designs is the wet well/dry well design.

18.6.4.1 Wet Well–Dry Well Pumping Stations

The wet well–dry well pumping station consists of two separate spaces or sections separated by a common wall. Wastewater is collected in one section (known as the wet well section); the pumping equipment (and in many cases, the motors and controllers) is located in a second section known as the dry well. There are many different designs for this type of system, but in most cases the pumps selected for this system are of a centrifugal design. There are a couple of major considerations in selecting centrifugal design:

1. This design allows for the separation of mechanical equipment (pumps, motors, controllers, wiring, etc.) from the potentially corrosive atmosphere (sulfides) of the wastewater.
2. This type of design is usually safer for workers because they can monitor, maintain, operate, and repair equipment without entering the pumping station wet well.

Note: Most pumping station wet wells are confined spaces. To ensure safe entry into such spaces, compliance with Occupational Safety and Health Administration's 29 CFR 1910.146 (Confined Space Entry Standard) is required.

18.6.4.2 Wet Well Pumping Stations

Another type of pumping station design is the wet well type. This type consists of a single compartment that collects the wastewater flow. The pump is submerged in the wastewater with motor controls located in the space or has a weatherproof motor housing located above the wet well. In this type of station, a submersible centrifugal pump is normally used.

18.6.4.3 Pneumatic Pumping Stations

The pneumatic pumping station consists of a wet well and a control system that controls the inlet and outlet value operations and provides pressurized air to force or push the wastewater through the system. The exact method of operation depends on the system design. When operating, wastewater in the wet well reaches a predetermined level and activates an automatic valve that closes the influent line. The tank (wet well) is then pressurized to a predetermined level. When the pressure reaches the predetermined level, the effluent line valve is opened and the pressure pushes the wastestream out the discharge line.

18.6.4.4 Pumping Station Wet Well Calculations

Calculations normally associated with pumping station wet well design (determining design lift or pumping capacity, etc.) are usually left up to design and mechanical engineers. However, on occasion, wastewater operators or interceptor's technicians may be called upon to make certain basic calculations. Usually these calculations deal with determining either pump capacity without influent (e.g., to check the pumping rate of the station's constant speed pump) or pump capacity with influent (e.g., to check how many gallons per minute the pump is discharging). In this section we use examples to describe instances on how and where these two calculations are made.

Example 18.7: Determining Pump Capacity without Influent

Problem:

A pumping station wet well is 10 × 9 ft. The operator needs to check the pumping rate of the station's constant speed pump. To do this, the influent valve to the wet well is closed for a 5-min test, and the level in the well dropped 2.2 ft. What is the pumping rate in gallons per minute?

Solution:

Using the length and width of the well, we can find the area of the water surface:

$$10 \text{ ft} \times 9 \text{ ft} = 90 \text{ ft}^2$$

The water level dropped 2.2 ft. From this we can find the volume of water removed by the pump during the test:

$$A \times D = v$$

$$90 \text{ ft}^2 \times 2.2 \text{ ft} = 198 \text{ ft}$$

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One cubic foot of water holds 7.48 gal. We can convert this volume in cubic feet to gallons:

$$198\ \text{ft}^3 \times \frac{7.48\ \text{gal}}{1\ \text{ft}^3} = 1481\ \text{gal}$$

The test was done for 5 min. From this information, a pumping rate can be calculated:

$$\frac{1481\ \text{gal}}{5\ \text{min}} = \frac{296.2}{1\ \text{min}} 296.2\ \text{gal/min}$$

Example 18.8: Determining Pump Capacity with Influent

Problem:

A wet well is 8.2 × 9.6 ft. The influent flow to the well, measured upstream, is 365 gal/min. If the wet well rises 2.2 in. in 5 min, how many gallons per minute is the pump discharging?

Solution:

$$\text{Influent} = \text{Discharge} + \text{Accumulation}$$

$$\frac{365\ \text{gal}}{1\ \text{min}} = \text{Discharge} + \text{Accumulation}$$

We want to calculate the discharge. Influent is known and we have enough information to calculate the accumulation.

$$\text{Volume accumulated} = 8.2\ \text{ft} \times 9.6\ \text{ft} \times 2.2\ \text{in.} \times \frac{1\ \text{ft}}{12\ \text{in.}} \times \frac{7.48\ \text{gal}}{1\ \text{ft}^3} = 108\ \text{gal}$$

$$\text{Accumulation} = \frac{108\ \text{gal}}{5\ \text{min}} = \frac{21.6\ \text{gal}}{1\ \text{min}} = 21.6\ \text{gal/min}$$

Using Equation 18.7:

$$\text{Influent} = \text{Discharge} + \text{Accumulation}$$

$$365\ \text{gal/min} = \text{Discharge} + 21.6$$

Subtracting from both sides:

$$365\ \text{gal/min} - 21.6\ \text{gal/min} = \text{Discharge} + 21.6\ \text{gal/min} - 21.6\ \text{gal/min}$$

$$343.4\ \text{gal/min} = \text{Discharge}$$

The wet well pump is discharging 343.4 gal each minute.

18.7 PRELIMINARY TREATMENT

The initial stage in the wastewater treatment process (following collection and influent pumping) is preliminary treatment. Raw influent entering the treatment plant may contain many kinds of materials (trash). The purpose of preliminary treatment is to protect plant equipment by removing these materials that could cause clogs, jams, or excessive wear to plant machinery. In addition, the removal of various materials at the beginning of the treatment process saves valuable space within the treatment plant.

Preliminary treatment may include many different processes. Each is designed to remove a specific type of material — a potential problem for the treatment process. Processes include: wastewater collections (influent pumping, screening, shredding, grit removal, flow measurement, preaeration, chemical addition, and flow equalization). The major processes are shown in Figure 18.1. In this section, we describe and discuss each of these processes and their importance in the treatment process.

Note: As mentioned, not all treatment plants will include all of the processes shown in Figure 18.1. Specific processes have been included to facilitate discussion of major potential problems with each process and its operation; this is information that may be important to the wastewater operator.

18.7.1 Screening

The purpose of screening is to remove large solids, such as rags, cans, rocks, branches, leaves, roots, etc., from the flow before the flow moves on to downstream processes.

Note: Typically, a treatment plant will remove anywhere from 0.5 to 12 ft^3 of screenings for each million gallons of influent received.

A bar screen traps debris as wastewater influent passes through. Typically, a bar screen consists of a series of parallel, evenly spaced bars or a perforated screen placed in a channel (see Figure 18.2). The wastestream passes through the screen and the large solids (screenings) are trapped on the bars for removal.

Note: The screenings must be removed frequently enough to prevent accumulation that will block the screen and cause the water level in front of the screen to build up.

The bar screen may be coarse (2 to 4-in. openings) or fine (0.75 to 2.0-in. openings). The bar screen may be manually cleaned (bars or screens are placed at an angle of 30° for easier solids removal; see Figure 18.2) or mechanically cleaned (bars are placed at 45° to 60° angle to improve mechanical cleaner operation).

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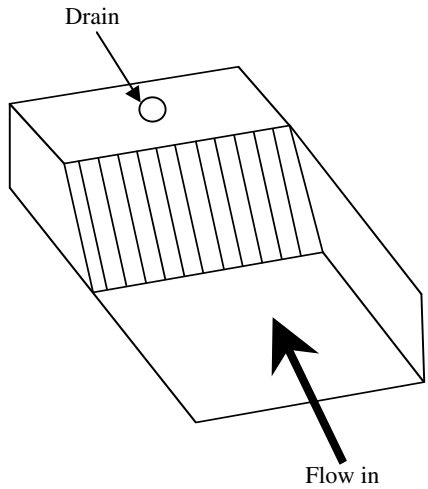

FIGURE 18.2 Bar screen. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

The screening method employed depends on the design of the plant, the amount of solids expected, and whether the screen is for constant or emergency use only.

18.7.1.1 Manually Cleaned Screens

Manually cleaned screens are cleaned at least once per shift (or often enough to prevent buildup that may cause reduced flow into the plant) using a long tooth rake. Solids are manually pulled to the drain platform and allowed to drain before storage in a covered container.

The area around the screen should be cleaned frequently to prevent a buildup of grease or other materials that can cause odors, slippery conditions, and insect and rodent problems. Because screenings may contain organic matter as well as large amounts of grease they should be stored in a covered container. Screenings can be disposed of by burial in approved landfills or by incineration. Some treatment facilities grind the screenings into small particles; these particles are then returned to the wastewater flow for further processing and removal later in the process.

18.7.1.1.1 Operational Problems

Manually cleaned screens require a certain amount of operator attention to maintain optimum operation. Failure to clean the screen frequently can lead to septic wastes entering the primary, surge flows after cleaning, and low flows before cleaning. On occasion, when such operational problems occur, it becomes necessary to increase the frequency of the cleaning cycle. Another operational problem is excessive grit in the bar screen channel. Improper design or construction or insufficient cleaning may cause this problem. The corrective action required is either to correct the design problem or increase cleaning frequency and flush the channel regularly. Another common problem with manually cleaned bar screens is their tendency to clog frequently. This may be caused by excessive debris in the wastewater or the screen being too fine for its current application. The operator should locate the source of the excessive debris and eliminate it. If the screen is the problem, a coarser screen may need to be installed. If the bar screen area is filled with obnoxious odors, flies, and other insects, it may be necessary to dispose of screenings more frequently.

18.7.1.2 Mechanically Cleaned Screens

Mechanically cleaned screens use a mechanized rake assembly to collect the solids and move them (carry them) out of the wastewater flow for discharge to a storage hopper. The screen may be continuously cleaned or cleaned on a time or flow controlled cycle. As with the manually cleaned screen, the area surrounding the mechanically operated screen must be cleaned frequently to prevent buildup of materials, which can cause unsafe conditions.

As with all mechanical equipment, operator vigilance is required to ensure proper operation and proper maintenance. Maintenance includes lubricating equipment and maintaining it in accordance with manufacturer's recommendations or the plant's O & M manual.

Screenings from mechanically operated barscreens are disposed of in the same manner as screenings from manually operated screens. These include landfill disposal, incineration, or the process of grinding into smaller particles for return to the wastewater flow.

18.7.1.2.1 Operational Problems

Many of the operational problems associated with mechanically cleaned bar screens are the same as those for manual screens. These include septic wastes entering the primary, surge flows after cleaning, excessive grit in the bar screen channel, and a screen that clogs frequently. Basically the same corrective actions employed for manually operated screens would be applied for these problems in mechanically operated screens. In addition to these problems, mechanically operated screens also have other problems. These include the cleaner failing to operate; and a nonoperating rake, but operating motor. Obviously, these are mechanical problems that could be caused by jammed cleaning mechanism, broken chain, broken cable, or a broken shear pin. Authorized and fully trained maintenance operators should be called in to handle these types of problems.

18.7.1.3 Safety

The screening area is the first location where the operator is exposed to the wastewater flow. Any toxic, flammable or explosive gases present in the wastewater can be released at this point. Operators who frequent enclosed bar screen areas should be equipped with personal air monitors. Adequate ventilation must be provided. It is also

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important to remember that, due to the grease attached to the screenings this area of the plant can be extremely slippery. Routine cleaning is required to minimize this problem.

Note: Never override safety devices on mechanical equipment. Overrides can result in dangerous conditions, injuries, and major mechanical failure.

18.7.1.4 Screenings Removal Computations

Operators responsible for screenings disposal are typically required to keep a record of the amount of screenings removed from the wastewater flow. To keep and maintain accurate screenings' records, the volume of screenings withdrawn must be determined. Two methods are commonly used to calculate the volume of screenings withdrawn:

$$\text{Screenings Removed}\left(\text{ft}^3/\text{d}\right) = \frac{\text{Screenings}\left(\text{ft}^3\right)}{\text{d}} \quad (18.6)$$

$$\text{Screenings Removed}\left(\text{ft}^3/\text{MG}\right) = \frac{\text{Screenings}\left(\text{ft}^3\right)}{\text{Q (MG)}} \quad (18.7)$$

EXAMPLE 18.9

Problem:

A total of 65 gal of screenings are removed from the wastewater flow during a 24-h period. What is the screenings removal reported as cubic feet per day?

Solution:

First, convert gallons screenings to cubic feet:

$$\frac{65\ \text{gal}}{7.48\ \text{gal}/\text{ft}^3} = 8.7\ \text{ft}^3\ \text{screenings}$$

Next, calculate screenings removed as cubic feet per day:

$$\text{Screenings Removed}\left(\text{ft}^3/\text{d}\right) = \frac{8.7\ \text{ft}^3}{1\ \text{d}} = 8.7\ \text{ft}^3/\text{d}$$

EXAMPLE 18.10

Problem:

During 1 week, a total of 310 gal of screenings were removed from the wastewater screens. What is the average screening removal in cubic feet per day?

Solution:

First, gallons screenings must be converted to cubic feet screenings:

$$\frac{310\ \text{gal}}{7.48\ \text{gal}/\text{ft}^3} = 41.4\ \text{ft}^3\ \text{screenings}$$

Next, calculate screenings removed as cubic feet per day:

$$\text{Screenings Removed}\left(\text{ft}^3/\text{d}\right) = \frac{41.4\ \text{ft}^3}{7\ \text{d}} = 5.9\ \text{ft}^3/\text{d}$$

18.7.2 SHREDDING

As an alternative to screening, shredding can be used to reduce solids to a size that can enter the plant without causing mechanical problems or clogging. Shredding processes include comminution (comminute means cut up) and barminution devices.

18.7.2.1 Comminution

The comminutor is the most common shredding device used in wastewater treatment. In this device all the wastewater flow passes through the grinder assembly. The grinder consists of a screen or slotted basket, a rotating or oscillating cutter, and a stationary cutter. Solids pass through the screen and are chopped or shredded between the two cutters. The comminutor will not remove solids, which are too large to fit through the slots, and it will not remove floating objects. These materials must be removed manually.

Maintenance requirements for comminutors include aligning, sharpening and replacing cutters and corrective and preventive maintenance performed in accordance with plant O & M manual.

18.7.2.1.1 Operational Problems

Common operational problems associated with comminutors include output containing coarse solids. When this occurs it is usually a sign that the cutters are dull or misaligned. If the system does not operate at all, the unit is either clogged, jammed, a shear pin or coupling is broken or electrical power is shut off. If the unit stalls or jams frequently, this usually indicates cutter misalignment, excessive debris in influent, or dull cutters.

Note: Only qualified maintenance operators should perform maintenance of shredding equipment.

18.7.2.2 Barminution

In barminution, the barminutor uses a bar screen to collect solids that are shredded and passed through the bar screen

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for removal at a later process. In operation each device's cutter alignment and sharpness are critical factors in effective operation. Cutters must be sharpened or replaced and alignment must be checked in accordance with manufacturer's recommendations. Solids, which are not shredded, must be removed daily, stored in closed containers, and disposed of by burial or incineration.

Barminutor operational problems are similar to those listed above for comminutors. Preventive and corrective maintenance as well as lubrication must be performed by qualified personnel and in accordance with the plant's O & M manual. Because of higher maintenance requirements the barminutor is less frequently used.

18.7.3 Grit Removal

The purpose of grit removal is to remove the heavy inorganic solids that could cause excessive mechanical wear. Grit is heavier than inorganic solids and includes, sand, gravel, clay, egg shells, coffee grounds, metal filings, seeds, and other similar materials.

There are several processes or devices used for grit removal. All of the processes are based on the fact that grit is heavier than the organic solids, which should be kept in suspension for treatment in following processes. Grit removal may be accomplished in grit chambers or by the centrifugal separation of sludge. Processes use gravity and velocity, aeration, or centrifugal force to separate the solids from the wastewater.

18.7.3.1 Gravity and Velocity Controlled Grit Removal

Gravity and velocity controlled grit removal is normally accomplished in a channel or tank where the speed or the velocity of the wastewater is controlled to about 1 foot per second (ideal), so that grit will settle while organic matter remains suspended. As long as the velocity is controlled in the range of 0.7 to 1.4 ft/sec the grit removal will remain effective. Velocity is controlled by the amount of water flowing through the channel, the depth of the water in the channel, the width of the channel, or the cumulative width of channels in service.

18.7.3.1.1 Process Control Calculations

Velocity of the flow in a channel can be determined either by the float and stopwatch method or by channel dimensions.

Example 18.11: Velocity by Float and Stopwatch

$$\text{Velocity, feet/second} = \frac{\text{Distance Traveled, feet}}{\text{Time Required, Seconds}}$$

Problem:

A float takes 25 sec to travel 34 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$V\ (\text{ft/sec}) = \frac{34\ \text{ft}}{25\ \text{sec}}$$

$$= 1.4\ \text{ft/sec}$$

Example 18.12: Velocity by Flow and Channel Dimensions

Note: This calculation can be used for a single channel or tank or multiple channels or tanks with the same dimensions and equal flow. If the flow through each unit of the unit dimensions is unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity, fps} = \frac{\text{Flow, MGD} \times 1.55\ \text{cfs/MGD}}{\#\text{Chan. in Ser.} \times \text{Chan Width, ft} \times \text{Water D, ft}}$$

Problem:

The plant is currently using two grit channels. Each channel is 3 ft wide and has a water depth of 1.2 ft. What is the velocity when the influent flow rate is 3.0 MGD?

Solution:

$$V\ (\text{ft/sec}) = \frac{3.0\ \text{MGD} \times 1.55\ \text{ft}^3/\text{sec/MGD}}{2\ \text{Channels} \times 3\ \text{ft} \times 1.2\ \text{ft}}$$

$$= \frac{4.65\ \text{ft}^3/\text{sec}}{7.2\ \text{ft}^2}$$

$$= 0.65\ \text{ft/sec}$$

Note: The channel dimensions must always be in feet. Convert inches to feet by dividing by 12 in./ft.

Example 18.13: Required Settling Time

Note: This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. In order to compute the settling time, the settling velocity in feet per second must be provided or determined experimentally in a laboratory.

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$$\text{Settling Time, seconds} = \frac{\text{Liquid Depth in Feet}}{\text{Settling, Velocity, fps}}$$

Problem:

The plant's grit channel is designed to remove sand and has a settling velocity of 0.085 ft/sec. The channel is currently operating at a depth of 2.2 ft. How many seconds will it take for a sand particle to reach the channel bottom?

Solution:

$$\text{Settling Time (sec)} = \frac{2.2 \text{ ft}}{0.085 \text{ ft/sec}}$$

$$= 25.9 \text{ sec}$$

Example 18.14: Required Channel Length

Note: This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity.

$$\text{Required Channel Length} = \frac{\text{Channel Depth, ft} \times \text{Flow Velocity, fps}}{\text{Settling Velocity, fps}}$$

Problem:

The plant's grit channel is designed to remove sand and has a settling velocity of 0.070 ft/sec. The channel is currently operating at a depth of 3 ft. The calculated velocity of flow through the channel is 0.80 ft/sec. The channel is 35 ft long. Is the channel long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length (ft)} = \frac{3 \text{ ft} \times 0.80 \text{ ft/sec}}{0.070 \text{ ft/sec}}$$

$$= 34.3 \text{ ft}$$

Yes, the channel is long enough to ensure all of the sand will be removed.

18.7.3.1.2 Cleaning

Gravity type systems may be manually or mechanically cleaned. Manual cleaning normally requires that the channel be taken out of service, drained, and manually cleaned. Mechanical cleaning systems are operated continuously or on a time cycle. Removal should be frequent enough to prevent grit carryover into the rest of the plant.

Note: Always ventilate the area thoroughly before and during cleaning activities.

18.7.3.1.3 Operational Observations/ Problems/Troubleshooting

Gravity and velocity-controlled grit removal normally occurs in a channel or tank where the speed or the velocity of the wastewater is controlled to about 1 ft/sec (ideal), so that grit settles while organic matters remains suspended. As long as the velocity is controlled in the range of 0.7 to 1.4 ft/sec, the grit removal remains effective. Velocity is controlled by the amount of water flowing through the channel, the depth of the water in the channel, by the width of the channel, or the cumulative width of channels in service.

During operation, the operator must pay particular attention to grit characteristics for evidence of organic solids in the channel, for evidence of grit carryover into plant, for evidence of mechanical problems, and for grit storage and disposal (housekeeping).

Aerated grit removal systems use aeration to keep the lighter organic solids in suspension while allowing the heavier grit articles to settle out. Aerated grit removal may be manually or mechanically cleaned; the majority of the systems are mechanically cleaned.

During normal operation, adjusting the aeration rate produces the desired separation. This requires observation of mixing and aeration and sampling of fixed suspended solids. Actual grit removal is controlled by the rate of aeration. If the rate is too high, all of the solids remain in suspension. If the rate is too low, both grit and organics will settle out.

The operator observes the same kinds of conditions as those listed for the gravity and velocity-controlled system, but must also pay close attention to the air distribution system to ensure proper operation.

The cyclone degritter uses a rapid spinning motion (centrifugal force) to separate the heavy inorganic solids or grit from the light organic solids. This unit process is normally used on primary sludge rather than the entire wastewater flow. This critical control factor for the process is the inlet pressure. If the pressure exceeds the recommendations of the manufacturer, the unit will flood and grit will carry through with the flow.

Grit is separated from flow, washed, and discharged directly to a strange container. Grit removal performance is determined by calculating the percent removal for inorganic (fixed) suspended solids.

The operator observes the same kinds of conditions listed for the gravity and velocity-controlled and aerated grit removal systems, with the exception of the air distribution system.

Typical problems associated with grit removal include mechanical malfunctions and rotten egg odor in the grit chamber (hydrogen sulfide formation), which can lead to metal and concrete corrosion problems. Low recovery rate of grit is another typical problem. Bottom scour, over-aeration, or a lack of detention time normally causes this.

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When these problems occur, the operator must make the required adjustments or repairs to correct the problems.

18.7.3.2 Grit Removal Calculations

Wastewater systems typically average 1 to 15 ft^3 of grit/MG of flow (sanitary systems average 1 to 4 ft^3/MG; combined wastewater systems average from 4 to 15 ft^3/MG of flow), with higher ranges during storm events.

Generally, grit is disposed of in sanitary landfills. Because of this practice, for planning purposes, operators must keep accurate records of grit removal. Most often, the data is reported as cubic feet of grit removed per million gallons of flow:

$$\text{Grit Removed}\left(\text{ft}^3/\text{MG}\right) = \frac{\text{Grit Volume}\left(\text{ft}^3\right)}{\text{Q (MG)}} \quad (18.8)$$

Over a given period, the average grit removal rate at a plant (at least a seasonal average) can be determined and used for planning purposes. Typically, grit removal is calculated as cubic yards because excavation is normally expressed in terms of cubic yards:

$$\text{Grit Removal}\left(\text{yd}^3\right) = \frac{\text{Total Grit}\left(\text{ft}^3\right)}{27\left(\text{ft}^3/\text{yd}^3\right)} \quad (18.9)$$

Example 18.15

Problem:

A treatment plant removes 10 ft^3 of grit in 1 d. How many cubic feet of grit are removed per million gallons if the plant flow was 9 MGD?

Solution:

$$\text{Grit Removed}\left(\text{ft}^3/\text{MG}\right) = \frac{\text{Grit Volume}\left(\text{ft}^3\right)}{\text{Q (MG)}}$$

$$= \frac{10\ \text{ft}^3}{9\ \text{MGD}}$$

$$= 1.1\ \text{ft}^3/\text{MGD}$$

Example 18.16

Problem:

The total daily grit removed for a plant is 250 gal. If the plant flow is 12.2 MGD, how many cubic feet of grit are removed per million gallons of flow?

Solution:

First, convert gallon grit removed to cubic feet:

$$\frac{250\ \text{gal}}{7.48\ \text{gal}/\text{ft}^3} = 33\ \text{ft}^3$$

Next, complete the calculation of cubic feet per million gallons:

$$\text{Grit Removed}\left(\text{ft}^3/\text{MG}\right) = \frac{\text{Grit Volume}\left(\text{ft}^3\right)}{\text{Q (MG)}}$$

$$= \frac{33\ \text{ft}^3}{12.2\ \text{MGD}}$$

$$= 2.7\ \text{ft}^3/\text{MGD}$$

Example 18.17

Problem:

The monthly average grit removal is 2.5 ft^3/MGD. If the monthly average flow is 2,500,000 gal/d, how many cubic yards must be available for grit disposal pit to have a 90-d capacity?

Solution:

First, calculate the grit generated each day:

$$\frac{2.5\ \text{ft}^3}{1\ \text{MG}} \times 2.5\ \text{MGD} = 6.25\ \text{ft}^3/\text{d}$$

The cubic feet grit generated for 90 d would be:

$$\frac{6.25\ \text{ft}^3}{1\ \text{d}} \times 90\ \text{d} = 562.5\ \text{ft}^3$$

Convert cubic feet grit to cubic yard grit:

$$\frac{562.5\ \text{ft}^3}{27\ \text{ft}^3/\text{yd}^3} = 21\ \text{yd}^3$$

18.7.4 Preaeration

In the preaeration process (diffused or mechanical), we aerate wastewater to achieve and maintain an aerobic state (to freshen septic wastes), strip off hydrogen sulfide (to reduce odors and corrosion), agitate solids (to release trapped gases and improve solids separation and settling), and to reduce BOD. All of this can be accomplished by aerating the wastewater for 10 to 30 min. To reduce BOD, preaeration must be conducted from 45 to 60 min.

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18.7.4.1 Operational Observations, Problems, and Troubleshooting

In preaeration grit removal systems, the operator is concerned with maintaining proper operation and must be alert to any possible mechanical problems. In addition, the operator monitors DO levels and the impact of preaeration on influent.

18.7.5 Chemical Addition

Chemical addition is made (either via dry chemical metering or solution feed metering) to the wastestream to improve settling, reduce odors, neutralize acids or bases, reduce corrosion, reduce BOD, improve solids and grease removal, reduce loading on the plant, add or remove nutrients, add organisms, and aid subsequent downstream processes. The particular chemical and amount used depends on the desired result. Chemicals must be added at a point where sufficient mixing will occur to obtain maximum benefit. Chemicals typically used in wastewater treatment include chlorine, peroxide, acids and bases, miner salts (ferric chloride, alum, etc.), and bioadditives and enzymes.

18.7.5.1 Operational Observations, Problems, and Troubleshooting

In adding chemicals to the wastestream to remove grit, the operator monitors the process for evidence of mechanical problems and takes proper corrective actions when necessary. The operator also monitors the current chemical feed rate and dosage. The operator ensures that mixing at the point of addition is accomplished in accordance with standard operating procedures and monitors the impact of chemical addition on influent.

18.7.6 Equalization

The purpose of flow equalization (whether by surge, diurnal, or complete methods) is to reduce or remove the wide swings in flow rates normally associated with wastewater treatment plant loading; it minimizes the impact of storm flows. The process can be designed to prevent flows above maximum plant design hydraulic capacity, reduce the magnitude of diurnal flow variations, and eliminate flow variations. Flow equalization is accomplished using mixing or aeration equipment, pumps, and flow measurement. Normal operation depends on the purpose and requirements of the flow equalization system. Equalized flows allow the plant to perform at optimum levels by providing stable hydraulic and organic loading. The downside to flow equalization is the additional costs associated with construction and operation of the flow equalization facilities.

18.7.6.1 Operational Observations, Problems, and Troubleshooting

During normal operations, the operator must monitor all mechanical systems involved with flow equalization and must watch for mechanical problems and take the appropriate corrective action. The operator also monitors DO levels, the impact of equalization on influent, and water levels in equalization basins; any necessary adjustments are also made.

18.7.7 Aerated Systems

Aerated grit removal systems use aeration to keep the lighter organic solids in suspension while allowing the heavier grit particles to settle out. Aerated grit removal may be manually or mechanically cleaned; the majority of the systems are mechanically cleaned.

In normal operation, the aeration rate is adjusted to produce the desired separation, which requires observation of mixing and aeration and sampling of fixed suspended solids. Actual grit removal is controlled by the rate of aeration. If the rate is too high, all of the solids remain in suspension. If the rate is too low, both the grit and the organics will settle out.

18.7.8 Cyclone Degritter

The cyclone degritter uses a rapid spinning motion (centrifugal force) to separate the heavy inorganic solids or grit from the light organic solids. This unit process is normally used on primary sludge rather than the entire wastewater flow. The critical control factor for the process is the inlet pressure. If the pressure exceeds the recommendations of the manufacturer, the unit will flood and grit will carry through with the flow. Grit is separated from the flow and discharged directly to a storage container. Grit removal performance is determined by calculating the percent removal for inorganic (fixed) suspended solids.

18.7.9 Preliminary Treatment Sampling and Testing

During normal operation of grit removal systems (with the exception of the screening and shredding processes), the plant operator is responsible for sampling and testing as shown in Table 18.3.

18.7.10 Other Preliminary Treatment Process Control Calculations

The desired velocity in sewers in approximately 2 ft/sec at peak flow; this velocity normally prevents solids from settling from the lines. When the flow reaches the grit channel, the velocity should decrease to about 1 ft/sec to permit the heavy inorganic solids to settle. In the example

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TABLE 18.3
Sampling and Testing Grit Removal Systems

Process	Location	Test	Frequency
Grit removal (velocity)	Influent	Suspended solids (fixed)	Variable
	Channel	Depth of grit	Variable
	Grit	Total solids (fixed)	Variable
	Effluent	Suspended solids (fixed)	Variable
Grit removal (aerated)	Influent	Suspended solids (fixed)	Variable
	Channel	DO	Variable
	Grit	Total solids (fixed)	Variable
	Effluent	Suspended solids (fixed)	Variable
Chemical addition	Influent	Jar test	Variable
Preaeration	Influent	DO	Variable
	Effluent	DO	Variable
Equalization	Effluent	DO	Variable

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

calculations that follow, we describe how the velocity of the flow in a channel can be determined by the float and stopwatch method and by channel dimensions.

Example 18.18: Velocity by Float and Stopwatch

$$\text{Velocity, feet/second} = \frac{\text{Distance Traveled, ft}}{\text{Time required, seconds}}$$

Problem:
A float takes 30 sec to travel 37 ft in a grit channel. What is the velocity of the flow in the channel?

Solution:

$$V\ (\text{ft/sec}) = \frac{37\ \text{ft}}{30\ \text{sec}}$$

$$= 1.2\ \text{ft/sec}$$

Example 18.19: Velocity by Flow and Channel Dimensions

Note: This calculation can be used for a single channel or tank or for multiple channels or tanks with the same dimensions and equal flow. If the flow through each of the unit dimensions is unequal, the velocity for each channel or tank must be computed individually.

$$\text{Velocity, fps} = \frac{\text{Flow, MGD} \times 1.55\ \text{cfs/MGD}}{\#\ \text{Chan in Ser} \times \text{Chan Width, ft} \times \text{Water Depth, ft}}$$

Problem:

The plant is currently using two grit channels. Each channel is 3 ft wide and has a water depth of 1.3 ft. What is the velocity when the influent flow rate is 4.0 MGD?

Solution:

$$V\ (\text{ft/sec}) = \frac{4.0\ \text{MGD} \times 1.55\ \text{ft}^3/\text{sec/MGD}}{2\ \text{Channels} \times 3\ \text{ft} \times 1.3\ \text{ft}}$$

$$= \frac{6.2\ \text{ft}^3/\text{sec}}{7.8\ \text{ft}^2}$$

$$= 0.79\ \text{ft/sec}$$

Note: Because 0.79 is within the 0.7 to 1.4 level, the operator of this unit would not make any adjustments.

Note: The channel dimensions must always be in feet. Convert inches to feet by dividing by 12 in./ft.

Example 18.20: Required Settling Time

Note: This calculation can be used to determine the time required for a particle to travel from the surface of the liquid to the bottom at a given settling velocity. To compute the settling time, settling velocity in feet per second must be provided or determined by experiment in a laboratory.

$$\text{Settling Time, seconds} = \frac{\text{Liquid Depth in ft}}{\text{Settling, Velocity, fps}}$$

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Problem:

The plant's grit channel is designed to remove sand and has a settling velocity of 0.080 ft/sec. The channel is currently operating at a depth of 2.3 ft. How many seconds will it take for a sand particle to reach the channel bottom?

Solution:

$$\text{Settling Time (sec)} = \frac{2.3 \text{ ft}}{0.080 \text{ ft/sec}}$$

$$= 28.7 \text{ sec}$$

Example 18.21: Required Channel Length

Note: This calculation can be used to determine the length of channel required to remove an object with a specified settling velocity.

$$\text{Required Channel Length} = \frac{\text{Channel Depth, ft} \times \text{Flow Velocity, fps}}{0.080 \text{ fps}}$$

Problem:

The plant's grit channel is designed to remove sand and has a settling velocity of 0.080 ft/sec. The channel is currently operating at a depth of 3 ft. The calculated velocity of flow through the channel is 0.85 ft/sec. The channel is 36 ft long. Is the channel long enough to remove the desired sand particle size?

Solution:

$$\text{Required Channel Length (ft)} = \frac{3 \text{ ft} \times 0.85 \text{ ft/sec}}{0.080 \text{ ft/sec}}$$

$$= 31.9 \text{ ft}$$

Yes, the channel is long enough to ensure all of the sand will be removed.

18.8 PRIMARY TREATMENT (SEDIMENTATION)

The purpose of primary treatment (primary sedimentation or primary clarification) is to remove settleable organic and flotable solids. Normally, each primary clarification unit can be expected to remove 90 to 95% settleable solids, 40 to 60% TSS, and 25 to 35% BOD.

Note: Performance expectations for settling devices used in other areas of plant operation is normally expressed as overall unit performance rather than settling unit performance.

Sedimentation may be used throughout the plant to remove settleable and floatable solids. It is used in primary treatment, secondary treatment, and advanced wastewater treatment processes. In this section, we focus on primary treatment or primary clarification, which uses large basins in which primary settling is achieved under relatively quiescent conditions (see Figure 18.1). Within these basins, mechanical scrapers collect the primary settled solids into a hopper where they are pumped to a sludge-processing area. Oil, grease, and other floating materials (scum) are skimmed from the surface. The effluent is discharged over weirs into a collection trough.

18.8.1 Process Description

In primary sedimentation, wastewater enters a settling tank or basin. Velocity is reduced to approximately 1 ft/min.

Note: Notice that the velocity is based on minutes instead of seconds, as was the case in the grit channels. A grit channel velocity of 1 ft/sec would be 60 ft/min.

Solids that are heavier than water settle to the bottom, while solids that are lighter than water float to the top. Settled solids are removed as sludge and floating solids are removed as scum. Wastewater leaves the sedimentation tank over an effluent weir and on to the next step in treatment. Detention time, temperature, tank design, and condition of the equipment control the efficiency of the process.

18.8.1.1 Overview of Primary Treatment

1. Primary treatment reduces the organic loading on downstream treatment processes by removing a large amount of settleable, suspended, and floatable materials.
2. Primary treatment reduces the velocity of the wastewater through a clarifier to approximately 1 to 2 ft/min, so that settling and floatation can take place. Slowing the flow enhances removal of suspended solids in wastewater.
3. Primary settling tanks remove floated grease and scum, remove the settled sludge solids, and collect them for pumped transfer to disposal or further treatment.
4. Clarifiers used may be rectangular or circular. In rectangular clarifiers, wastewater flows from one end to the other, and the settled sludge is moved to a hopper at the one end, either by flights set on parallel chains or by a single bottom scraper set on a traveling bridge. Floating material (mostly grease and oil) is collected by a surface skimmer.

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5. In circular tanks, the wastewater usually enters at the middle and flows outward. Settled sludge is pushed to a hopper in the middle of the tank bottom, and a surface skimmer removes floating material.
6. Factors affecting primary clarifier performance include:
   A. Rate of flow through the clarifier
   B. Wastewater characteristics (strength; temperature; amount and type of industrial waste; and the density, size, and shapes of particles)
   C. Performance of pretreatment processes
   D. Nature and amount of any wastes recycled to the primary clarifier
7. Key factors in primary clarifier operation include the following concepts:

$$\text{Retention Time (h)} = \frac{\text{v (gal)} \times 24 \text{ h/d}}{\text{Q (gal/d)}}$$

$$\text{Surface Loading Rate } \left(\text{gal/d/ft}^2\right) = \frac{\text{Q (gal/d)}}{\text{Surface Area } \left(\text{ft}^2\right)}$$

$$\text{Solids Loading Rate } \left(\text{lb/d/ft}^2\right) = \frac{\text{Solids into Clarifier (lb/d)}}{\text{Surface Area } \left(\text{ft}^2\right)}$$

$$\text{Weir Overflow Rate (gal/d/lineal ft)} = \frac{\text{Q (gal/d)}}{\text{Weir Length (lineal ft)}}$$

18.8.2 Types of Sedimentation Tanks

Sedimentation equipment includes septic tanks, two story tanks, and plain settling tanks or clarifiers. All three devices may be used for primary treatment; plain settling tanks are normally used for secondary or advanced wastewater treatment processes.

18.8.2.1 Septic Tanks

Septic tanks are prefabricated tanks that serve as a combined settling and skimming tank and as an unheated–unmixed anaerobic digester. Septic tanks provide long settling times (6 to 8 h or more), but do not separate decomposing solids from the wastewater flow. When the tank becomes full, solids will be discharged with the flow. The process is suitable for small facilities (i.e., schools, motels, homes, etc.), but due to the long detention times and lack of control, it is not suitable for larger applications.

18.8.2.2 Two-Story (Imhoff) Tank

The two-story or Imhoff tank is similar to a septic tank in the removal of settleable solids and the anaerobic digestion of solids. The difference is that the two story tank consists of a settling compartment where sedimentation is accomplished, a lower compartment where settled solids and digestion takes place, and gas vents. Solids removed from the wastewater by settling pass from the settling compartment into the digestion compartment through a slot in the bottom of the settling compartment. The design of the slot prevents solids from returning to the settling compartment. Solids decompose anaerobically in the digestion section. Gases produced as a result of the solids decomposition are released through the gas vents running along each side of the settling compartment.

18.8.2.3 Plain Settling Tanks (Clarifiers)

The plain settling tank or clarifier optimizes the settling process. Sludge is removed from the tank for processing in other downstream treatment units. Flow enters the tank, is slowed and distributed evenly across the width and depth of the unit, passes through the unit, and leaves over the effluent weir. Detention time within the primary settling tank is from 1 to 3 h (2-h average).

Sludge removal is accomplished frequently on either a continuous or intermittent basis. Continuous removal requires additional sludge treatment processes to remove the excess water resulting from the removal of sludge, which contains less than 2 to 3% solids. Intermittent sludge removal requires the sludge be pumped from the tank on a schedule frequent enough to prevent large clumps of solids rising to the surface but infrequent enough to obtain 4 to 8% solids in the sludge withdrawn.

Scum must be removed from the surface of the settling tank frequently. This is normally a mechanical process, but may require manual start-up. The system should be operated frequently enough to prevent excessive buildup and scum carryover but not so frequent as to cause hydraulic overloading of the scum removal system.

Settling tanks require housekeeping and maintenance. Baffles (devices that prevent floatable solids and scum from leaving the tank), scum troughs, scum collectors, effluent troughs, and effluent weirs require frequent cleaning to prevent heavy biological growths and solids accumulations. Mechanical equipment must be lubricated and maintained as specified in the manufacturer's recommendations or in accordance with procedures listed in the plant O & M manual.

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Process control sampling and testing is used to evaluate the performance of the settling process. Settleable solids, DO, pH, temperature, TSS and BOD_5, as well as sludge solids and volatile matter testing are routinely accomplished.

18.8.3 Operator Observations, Process Problems, and Troubleshooting

Before identifying a primary treatment problem and proceeding with appropriate troubleshooting effort, the operator must be cognizant of what constitutes normal operation. (i.e., Is there a problem or is the system operating as per design?)

Several important items of normal operation can have a strong impact on performance. In the following section, we discuss the important operational parameters and normal observations.

18.8.3.1 Primary Clarification: Normal Operation

In primary clarification, wastewater enters a settling tank or basin. Velocity reduces to approximately 1 ft/min.

Note: Notice that the velocity is based on minutes instead of seconds, as was the case in the grit channels. A grit channel velocity of 1 ft/sec would be 60 ft/min.

Solids that are heavier than water settle to the bottom, while solids that are lighter than water float to the top. Settled solids are removed as sludge and floating solids are removed as scum. Wastewater leaves the sedimentation tank over an effluent weir and on to the next step in treatment. Detention time, temperature, tank design, and condition of the equipment control the efficiency of the process.

18.8.3.2 Primary Clarification: Operational Parameters (Normal Observations)

1. Flow distribution — Normal flow distribution is indicated by flow to each in-service unit being equal and uniform. There is no indication of short-circuiting. The surface-loading rate is within design specifications.
2. Weir condition — Under this condition, weirs are level, flow over the weir is uniform, and the weir overflow rate is within design specifications.
3. Scum removal — The surface is free of scum accumulations, and the scum removal does not operate continuously.
4. Sludge removal — No large clumps of sludge appear on the surface. The system operates as designed. The pumping rate is controlled to prevent coning or buildup, and the sludge blanket depth is within desired levels.
5. Performance — The unit is removing expected levels of BOD_5, TSS, and settleable solids.
6. Unit maintenance — Mechanical equipment is maintained in accordance with planned schedules; equipment is available for service as required.

To assist the operator in judging primary treatment operation, several process control tests can be used for process evaluation and control. These tests include the following:

1. pH (normal range: 6.5 to 9.0)
2. DO (normal range is <1.0 mg/L)
3. Temperature (varies with climate and season)
4. Settleable solids (influent is 5 to 15 mL/L; effluent is 0.3 to 5 mL/L)
5. BOD (influent is 150 to 400 mg/L; effluent is 50 to 150 mg/L)
6. Percent solids (4 to 8%)
7. Percent volatile matter (40% to 70%)
8. Heavy metals (as required)
9. Jar tests (as required)

Note: Testing frequency should be determined on the basis of the process influent and effluent variability and the available resources. All should be performed periodically to provide reference information for evaluation of performance.

18.8.4 Process Control Calculations

As with many other wastewater treatment plant unit processes, process control calculations aid in determining the performance of the sedimentation process. Process control calculations are used in the sedimentation process to determine:

1. Percent removal
2. Hydraulic detention time
3. Surface loading rate (surface settling rate)
4. Weir overflow rate (weir loading rate)
5. Sludge pumping
6. Percent total solids (% TS)

In the following sections, we take a closer look at a few of these process control calculations and example problems.

Note: The calculations presented in the following sections allow you to determine values for each function performed. Keep in mind that an optimally operated primary clarifier should have values in an expected range.

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18.8.4.1 Percent Removal

The expected range of percent removal for a primary clarifier is:

Settleable solids	90–95%
Suspended solids	40–60%
BOD	25–35%

18.8.4.2 Detention Time

The primary purpose of primary settling is to remove settleable solids. This accomplished by slowing the flow down to approximately 1 ft/min. The flow at this velocity will stay in the primary tank from 1.5 to 2.5 h. The length of time the water stays in the tank is called the hydraulic detention time.

18.8.4.3 Surface Loading Rate (Surface Settling Rate and Surface Overflow Rate)

Surface loading rate is the number of gallons of wastewater passing over 1 ft^2 of tank/d. This can be used to compare actual conditions with design. Plant designs generally use a surface loading rate of 300 to 1200 gal/d/ ft^2.

Other terms used synonymously with surface loading rate are surface overflow rate and surface settling rate. The equation for calculating the surface loading rate is as follows:

$$\text{Surface Loading Rate}\left(\text{gal/d/ft}^2\right) = \frac{Q\ (\text{gal/d})}{\text{Settling Tank Area}\left(\text{ft}^2\right)} \tag{18.10}$$

Example 18.22

Problem:

The settling tank is 120 ft in diameter and the flow to the unit is 4.5 MGD. What is the surface loading rate in gallons per day per square foot?

Solution:

$$\text{Surface Loading Rate}\left(\text{gal/d/ft}^2\right) = \frac{Q\ (\text{gal/d})}{\text{Settling Tank Area}\left(\text{ft}^2\right)} = \frac{4.5\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MGD}}{0.785 \times 120\ \text{ft} \times 120\ \text{ft}} = 398\ \text{gal/d/ft}^2$$

Example 18.23

Problem:

A circular clarifier has a diameter of 50 ft. If the primary effluent flow is 2,150,000 gal/d, what is the surface overflow rate in gallons per day per square foot?

Solution:

$$\text{Surface Overflow Rate}\left(\text{gal/d/ft}^2\right) = \frac{Q\ (\text{gal/d})}{\text{Area}\left(\text{ft}^2\right)} = \frac{2{,}150{,}000}{0.785 \times 50\ \text{ft} \times 50\ \text{ft}} = 1096\ \text{gal/d/ft}^2$$

18.8.4.4 Weir Overflow Rate (Weir Loading Rate)

Weir overflow rate (weir loading rate) is the amount of water leaving the settling tank per linear foot of weir. The result of this calculation can be compared with design. Normally weir overflow rates of 10,000 to 20,000 gal/d/ft are used in the design of a settling tank:

$$\text{Weir Overflow Rate}\left(\text{gal/d/ft}^2\right) = \frac{Q\ (\text{gal/d})}{\text{Weir Length (ft)}} \tag{18.11}$$

Example 18.24

Problem:

The circular settling tank is 90 ft in diameter and has a weir along its circumference. The effluent flow rate is 2.55 MGD. What is the weir overflow rate in gallons per day per foot?

Solution:

$$\text{Weir Overflow Rate}\left(\text{gal/d/ft}^2\right) = \frac{2.55\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}}{3.14 \times 90\ \text{ft}} = 9023\ \text{gal/d/ft}$$

18.8.4.5 Sludge Pumping

Determination of sludge pumping (the quantity of solids and volatile solids removed from the sedimentation tank) provides accurate information needed for process control of the sedimentation process:

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$$\text{Solids Pumped (lb/d)} = \text{Pump Rate} \times \text{Pump Time} \times 8.34\ \text{lb/gal} \times \%\ \text{Solids} \quad (18.12)$$

$$\text{Volume of Solids (lb/d)} = \text{Pump Rate} \times \text{Pump Time} \times 8.34 \times \%\ \text{Solids} \times \%\ \text{VM} \quad (18.13)$$

EXAMPLE 18.25

Problem:

The sludge pump operates 20 min/h. The pump delivers 20 gal/min of sludge. Laboratory tests indicate that the sludge is 5.2% solids and 66% volatile matter. How many pounds of volatile matter are transferred from the settling tank to the digester?

Solution:

Pump Time = 20 min/h
Pump Rate = 20 gal/min
% Solids = 5.2%
% VM= 66%

$$\text{Volume of Solids (lb/d)} = 20\ \text{gal/min} \times (20\ \text{min/h} \times 24\ \text{h/d}) \times 8.34\ \text{lb/gal} \times 0.052 \times 0.66 = 2748\ \text{lb/d}$$

18.8.4.5.1 *Percent Total Solids*

EXAMPLE 18.26

Problem:

A settling tank sludge sample is tested for solids. The sample and dish weigh 74.69 g. The dish weighs 21.2 g. After drying, the dish with dry solids now weighs 22.3 g. What is the percent total solids (% TS) of the sample?

Solution:

Sample + Dish × Dish = Sample Weight
74.69 g × 21.2 g = 53.49 g
Dish + Dry Solids × Dish = Dry Solids Weight
22.3 g × 21.2 g = 1.1 g

$$\frac{1.1\ \text{g}}{53.49\ \text{g}} \times 100\% = 2\%$$

18.8.4.6 BOD and Suspended Solids Removal

To calculate the pounds of BOD or suspended solids (SS) removed each day, you need to know the milligrams per liter of BOD or suspended solids removed and the plant flow. Then you can use the milligrams per liter to pounds per day equation:

$$\text{SS Removed} = \text{mg/L} \times \text{MGD} \times 8.3\ \text{lb/gal} \quad (18.14)$$

EXAMPLE 18.27

Problem:

If 120 mg/L suspended solids are removed by a primary clarifier, how many pounds per day of suspended solids are removed when the flow is 6,230,000 gal/d?

Solution:

$$\text{SS Removed (lb/d)} = 120\ \text{mg/L} \times 6.25\ \text{MGD} \times 8.34\ \text{lb/gal} = 6255\ \text{lb/d}$$

EXAMPLE 18.28

Problem:

The flow to a secondary clarifier is 1.6 MGD. If the influent BOD concentration is 200 mg/L and the effluent BOD concentration is 70 mg/L, how many pounds of BOD are removed daily?

Solution:

Calculate the milligrams per liter of BOD removed:

$$\text{BOD removed (lb/d)} = 200\ \text{mg/L} \times 70\ \text{mg/L} = 130\ \text{mg/L}$$

Next calculate the pounds per day of BOD removed:

$$\text{BOD removed (lb/d)} = 130\ \text{mg/L} \times 1.6\ \text{MGD} \times 8.34\ \text{lb/gal} = 1735\ \text{lb/d}$$

18.8.5 PROBLEM ANALYSIS

In primary treatment (as is also clear in the operation of other unit processes), the primary function of the operator is to identify causes of process malfunctions, develop solutions, and prevent recurrence. In other words, the operator's goal is to perform problem analysis or troubleshooting on unit processes when required and to restore the unit processes to optimal operating condition. The immediate goal in problem analysis is to solve the immediate problem. The long-term goal is to ensure that the problem does not pop up again, causing poor performance in the future.

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In this section, we cover a few indicators and observations of operational problems with the primary treatment process. The observations presented are not all-inclusive, but highlight the most frequently confronted problems.

1. Poor suspended solids removal (primary clarifier)
   Causal factors:
   A. Hydraulic overload
   B. Sludge buildup in tanks and decreased volume and allows solids to scour out tanks
   C. Strong recycle flows
   D. Industrial waste concentrations
   E. Wind currents
   F. Temperature currents
2. Floating sludge
   Causal factors:
   A. Sludge becoming septic in tank
   B. Damaged or worn collection equipment
   C. Recycled waste sludge
   D. Primary sludge pumps malfunctions
   E. Sludge withdrawal line plugged
   F. Return of well-nitrified waste-activated sludge
   G. Too few tanks in service
   H. Damaged or missing baffles
3. Primary sludge solids concentration too low
   Causal factors:
   A. Hydraulic overload
   B. Overpumping of sludge
   C. Collection system problems
   D. Decreased influent solids loading
4. Septic wastewater or sludge
   Causal factors:
   A. Damaged or worn collection equipment
   B. Infrequent sludge removal
   C. Insufficient industrial pretreatment
   D. Septic sewage from collection system
   E. Strong recycle flows
   F. Primary sludge pump malfunction
   G. Sludge withdrawal line plugged
   H. Sludge collectors not run often enough
   I. Septage dumpers
5. Primary sludge solids concentrations too high
   Causal factors:
   A. Excessive grit and compacted material
   B. Primary sludge pump malfunction
   C. Sludge withdrawal line plugged
   D. SRT is too long
   E. Increased influent loadings

18.8.6 Effluent from Settling Tanks

Upon completion of screening, degritting, and settling in sedimentation basins, large debris, grit, and many settleable materials have been removed from the wastestream. What is left is referred to as primary effluent. Usually cloudy and frequently gray in color, primary effluent still contains large amounts of dissolved food and other chemicals (nutrients). These nutrients are treated in the next step in the treatment process, secondary treatment, which is discussed in the next section.

Note: Two of the most important nutrients left to remove are phosphorus and ammonia. While we want to remove these two nutrients from the wastestream, we do not want to remove too much. Carbonaceous microorganisms in secondary treatment (biological treatment) need both phosphorus and ammonia.

18.9 SECONDARY TREATMENT

The main purpose of secondary treatment (sometimes referred to as biological treatment) is to provide BOD removal beyond what is achievable by primary treatment. There are three commonly used approaches, and all take advantage of the ability of microorganisms to convert organic wastes (via biological treatment) into stabilized, low-energy compounds. Two of these approaches, the trickling filter (and its variation, the RBC) and the activated sludge process, sequentially follow normal primary treatment. The third, ponds (oxidation ponds or lagoons), can provide equivalent results without preliminary treatment.

In this section, we present a brief overview of the secondary treatment process followed by a detailed discussion of wastewater treatment ponds (used primarily in smaller treatment plants), trickling filters, and RBCs. We then shift focus to the activated sludge process, the secondary treatment process, which is used primarily in large installations and is the main focus of the handbook.

Secondary treatment refers to those treatment processes that use biological processes to convert dissolved, suspended, and colloidal organic wastes to more stable solids that can either be removed by settling or discharged to the environment without causing harm.

Exactly what is secondary treatment? As defined by the Clean Water Act (CWA), secondary treatment produces an effluent with nor more than 30 mg/L BOD and 30 mg/L TSS.

Note: The CWA also states that ponds and trickling filters will be included in the definition of secondary treatment even if they do not meet the effluent quality requirements continuously.

Most secondary treatment processes decompose solids aerobically, producing carbon dioxide, stable solids, and more organisms. Since solids are produced, all of the biological processes must include some form of solids removal (settling tank, filter, etc.).

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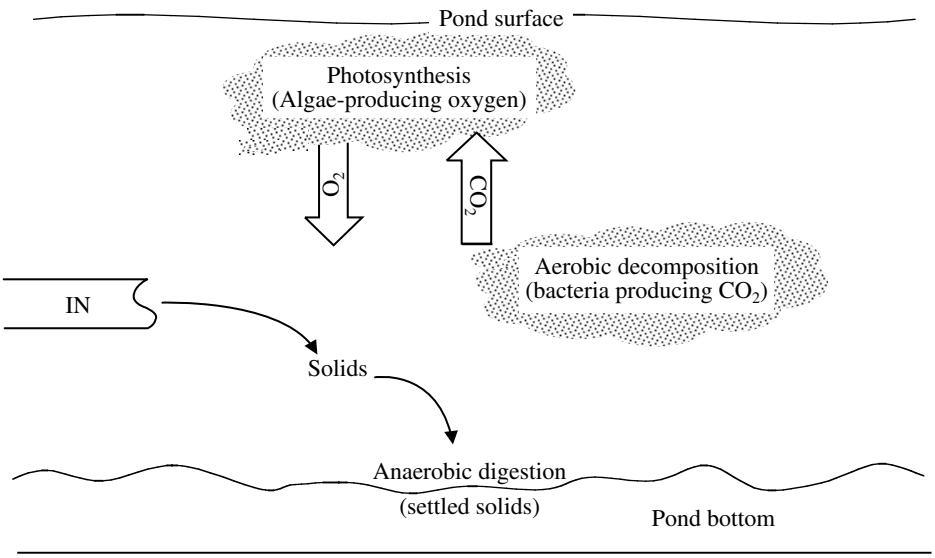

FIGURE 18.3 Stabilization pond processes. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Secondary treatment processes can be separated into two large categories: fixed film systems and suspended growth systems.

Fixed film systems are processes that use a biological growth (biomass or slime) that is attached to some form of media. Wastewater passes over or around the media and the slime. When the wastewater and slime are in contact, the organisms remove and oxidize the organic solids. The media may be stone, redwood, synthetic materials, or any other substance that is durable (capable of withstanding weather conditions for many years), provides a large area for slime growth and an open space for ventilation, and is not toxic to the organisms in the biomass. Fixed film devices include trickling filters and RBCs.

Suspended growth systems are processes that use a biological growth that is mixed with the wastewater. Typical suspended growth systems consist of various modifications of the activated sludge process.

18.9.1 Treatment Ponds

Wastewater treatment can be accomplished using ponds. Ponds are relatively easy to build and manage, can accommodate large fluctuations in flow, and can also provide treatment that approaches conventional systems (producing a highly purified effluent) at much lower cost. It is the cost (the economics) that drives many managers to decide on the pond option. The actual degree of treatment provided depends on the type and number of ponds used. Ponds can be used as the sole type of treatment or they can be used in conjunction with other forms of wastewater treatment (i.e., other treatment processes followed by a pond or a pond followed by other treatment processes).

18.9.1.1 Types of Ponds

Ponds can be classified (named) based upon their location in the system, the type wastes they receive, and the main biological process occurring in the pond. First we look at the types of ponds according to their location and the type wastes they receive: raw sewage stabilization ponds (see Figure 18.3), oxidation ponds, and polishing ponds. In the following section, we look at ponds classified by the type of processes occurring within the pond: Aerobic Ponds, anaerobic ponds, facultative ponds, and aerated ponds.

18.9.1.1.1 Ponds Based on Location and Types of Wastes They Receive

The types of ponds based on location and types of wastes they receive include raw sewage stabilization ponds, oxidation ponds, and polishing ponds.

18.9.1.1.1.1 Raw Sewage Stabilization Ponds

The raw sewage stabilization pond is the most common type of pond (see Figure 18.3). With the exception of screening and shredding, this type of pond receives no prior treatment. Generally, raw sewage stabilization ponds are designed to provide a minimum of 45 d detention time and to receive no more than 30 lb of BOD/d/acre. The quality of the discharge is dependent on the time of the year. Summer months produce high BOD removal, but excellent suspended solids removals.

The pond consists of an influent structure, pond berm, or walls and an effluent structure designed to permit selection of the best quality effluent. Normal operating depth of the pond is 3 to 5 ft.

The process occurring in the pond involves bacteria decomposing the organics in the wastewater (aerobically and anaerobically) and algae using the products of the

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bacterial action to produce oxygen (photosynthesis). Because this type of pond is the most commonly used in wastewater treatment, the process that occurs within the pond is described in greater detail below.

When wastewater enters the stabilization pond several processes begin to occur. These include settling, aerobic decomposition, anaerobic decomposition, and photosynthesis (see Figure 18.3). Solids in the wastewater will settle to the bottom of the pond. In addition to the solids in the wastewater entering the pond, solids, which are produced by the biological activity, will also settle to the bottom. Eventually this will reduce the detention time and the performance of the pond. When this occurs (usually 20 to 30 years) the pond will have to be replaced or cleaned.

Bacteria and other microorganisms use the organic matter as a food source. They use oxygen (aerobic decomposition), organic matter, and nutrients to produce carbon dioxide, water, stable solids (which may settle out), and more organisms. The carbon dioxide is an essential component of the photosynthesis process occurring near the surface of the pond.

Organisms also use the solids that settled out as food material. Because the oxygen levels at the bottom of the pond are extremely low the process used is anaerobic decomposition. The organisms use the organic matter to produce gases (hydrogen sulfide, methane, etc.), which are dissolved in the water; stable solids; and more organisms.

Near the surface of the pond a population of green algae will develop that can use the carbon dioxide produced by the bacterial population, nutrients, and sunlight to produce more algae and oxygen, which is dissolved into the water. The DO is then used by organisms in the aerobic decomposition process.

When compared with other wastewater treatment systems involving biological treatment, a stabilization pond treatment system is the simplest to operate and maintain. Operation and maintenance activities include collecting and testing samples for DO and pH, removing weeds and other debris (scum) from the pond, mowing the berms, repairing erosion, and removing burrowing animals.

Note: DO and pH levels in the pond will vary throughout the day. Normal operation will result in very high DO and pH levels because of the natural processes occurring.

Note: When operating properly the stabilization pond will exhibit a wide variation in both DO and pH. This is due to the photosynthesis occurring in the system.

18.9.1.1.1.2 Oxidation Ponds

An oxidation pond, which is normally designed using the same criteria as the stabilization pond, receives flows that have passed through a stabilization pond or primary settling tank. This type of pond provides biological treatment, additional settling, and some reduction in the number of fecal coliform present.

18.9.1.1.1.3 Polishing Ponds

A polishing pond, which uses the same equipment as a stabilization pond, receives flow from an oxidation pond or from other secondary treatment systems. Polishing ponds remove additional BOD, solids and fecal coliform and some nutrients. They are designed to provide 1 to 3 d detention time and normally operate at a depth of 5 to 10 ft. Excessive detention time or too shallow a depth will result in algae growth, which increases influent, suspended solids concentrations.

18.9.1.1.2 Ponds Based on the Type of Processes Occurring within the Ponds

The type of processes occurring within the pond may also classify ponds. These include the aerobic, anaerobic, facultative, and aerated processes.

18.9.1.1.2.1 Aerobic Ponds

In aerobic ponds, which are not widely used, oxygen is present throughout the pond. All biological activity is aerobic decomposition.

18.9.1.1.2.2 Anaerobic Ponds

Anaerobic ponds are normally used to treat high strength industrial wastes. No oxygen is present in the pond and all biological activity is anaerobic decomposition.

18.9.1.1.2.3 Facultative Ponds

The facultative pond is the most common type pond (based on processes occurring). Oxygen is present in the upper portions of the pond and aerobic processes are occurring. No oxygen is present in the lower levels of the pond where anoxic and anaerobic processes are occurring.

18.9.1.1.2.4 Aerated Ponds

In the aerated pond, oxygen is provided through the use of mechanical or diffused air systems. When aeration is used, the depth of the pond and the acceptable loading levels may increase. Mechanical or diffused aeration is often used to supplement natural oxygen production or to replace it.

18.9.1.2 Process Control Calculations (Stabilization Ponds)

Process control calculations are an important part of wastewater treatment operations, including pond operations. More significantly, process control calculations are an important part of state wastewater licensing examinations — you simply cannot master the licensing examinations without being able to perform the required calculations. Whenever possible, example process control problems are provided to enhance your knowledge and skills.

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18.9.1.2.1 Determining Pond Area in Acres

$$\text{Area (acres)} = \frac{\text{Area}\left(\text{ft}^2\right)}{43{,}560\ \text{ft}^2/\text{acre}} \tag{18.15}$$

18.9.1.2.2 Determining Pond Volume in Acre Feet

$$\text{v}\left(\text{acre-feet}\left[\text{ac-ft}\right]\right) = \frac{\text{v}\left(\text{ft}^3\right)}{43{,}560\ \text{ft}^2/\text{ac-ft}} \tag{18.16}$$

18.9.1.2.3 Determining Flow Rate in Acre Feet per Day

$$\text{Q, ac-ft/d} = \text{Q (MGD)} \times 3.069\ \text{ac-ft/MG} \tag{18.17}$$

Note: Acre-feet (ac-ft) is a unit that can cause confusion, especially for those not familiar with pond or lagoon operations. The measurement of 1 ac-ft is the volume of a box with a 1-acre top and 1 ft of depth — but the top does not have to be an even number of acres in size to use acre-feet.

18.9.1.2.4 Determining Flow Rate in Acre-Inches per Day

$$\text{Q (acre-inches/d)} = \text{Q (MGD)} \times 36.8\ \text{acre-inches/MG} \tag{18.18}$$

18.9.1.2.5 Hydraulic Detention Time in Days

$$\text{HDT (d)} = \frac{\text{Pond Volume (ac-ft)}}{\text{Influent Flow (ac-ft/d)}} \tag{18.19}$$

Note: Hydraulic detention time normally ranges from 30 to 120 d for stabilization ponds.

Example 18.29

Problem:

A stabilization pond has a volume of 53.5 ac-ft. What is the detention time in days when the flow is 0.30 MGD?

Solution:

Determine the flow rate in acre-feet per day:

$$\text{Q (ac-ft/d)} = 0.03\ \text{MGD} \times 3.069\ \text{ac-ft/MG}$$

$$= 0.92\ \text{ac-ft/d}$$

Determine the detention time:

$$\text{DT (d)} = \frac{53.5\ \text{acre}}{0.92\ \text{ac-ft/d}}$$

$$= 58.2\ \text{d}$$

18.9.1.2.6 Hydraulic Loading in Inches per Day (Overflow Rate)

$$\text{Hydraulic Loading (in./d)} = \frac{\text{Influent Flow (acre-inches/d)}}{\text{Pond Area (acres)}} \tag{18.20}$$

$$\text{Population Loading (people/acre/d)} = \frac{\text{Population Served by System (people)}}{\text{Pond Area (acres)}} \tag{18.21}$$

Note: Population loading normally ranges from 50 to 500 people per acre.

18.9.1.2.7 Organic Loading

Organic loading can be expressed as pounds of BOD per acre per day (most common), pounds BOD_5 per acre-foot per day, or people per acre per day.

$$\text{Organic L, lbs BOD/Acre/Day} = \frac{\text{BOD, mg/L} \times \text{Infl. flow, MGD} \times 8.34}{\text{Pond Area, Acres}} \tag{18.22}$$

Note: Normal range of organic loading is 10 to 50 lb BOD/d/acre.

Example 18.30

Problem:

A wastewater treatment pond has an average width of 380 ft and an average length of 725 ft. The influent flow rate to the pond is 0.12 MGD with a BOD concentration of 160 mg/L. What is the organic loading rate to the pond in pounds per day per acre?

Solution:

$$725\ \text{ft} \times 380\ \text{ft} \times \frac{1\ \text{acre}}{43{,}560\ \text{ft}^2} = 6.32\ \text{acre}$$

$$0.12\ \text{MGD} \times 160\ \text{mg/L} \times 8.34\ \text{lb/gal} = 106.1\ \text{lb/d}$$

$$\frac{160.1\ \text{lb/d}}{6.32\ \text{acre}} = 25.3\ \text{lb/d/acre}$$

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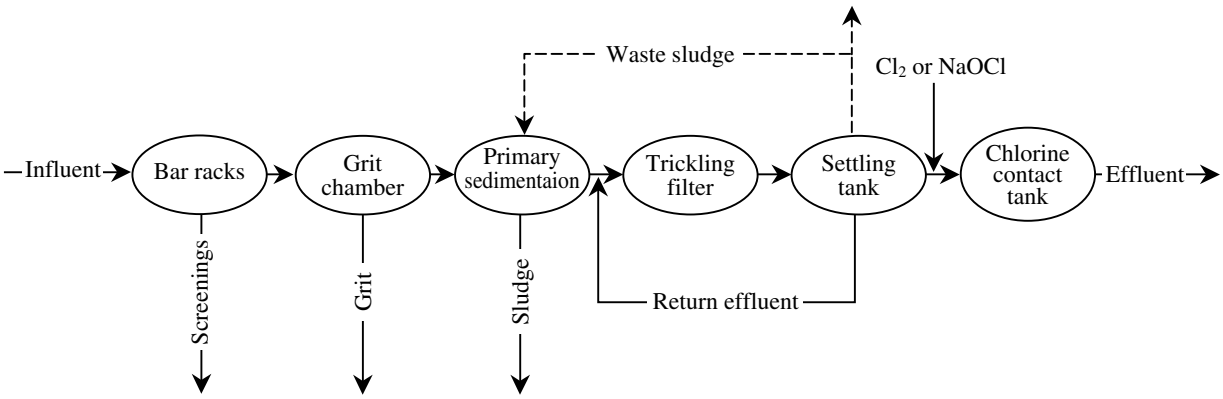

FIGURE 18.4 Simplified flow diagram of trickling filter used for wastewater treatment. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

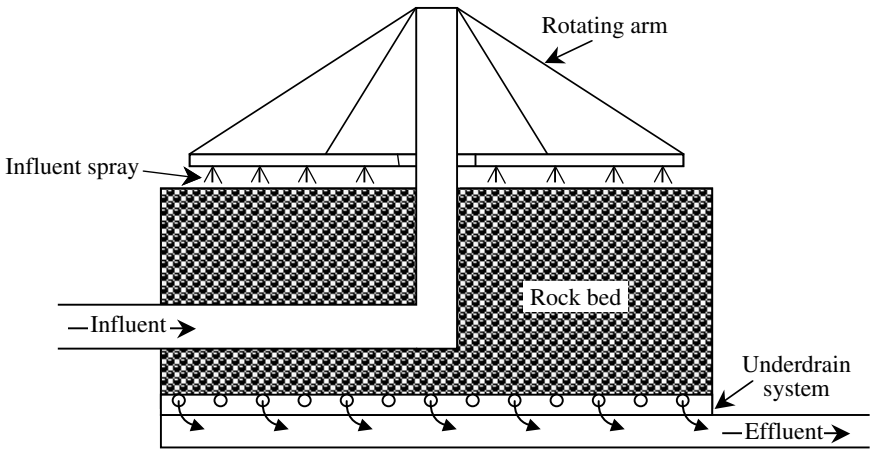

FIGURE 18.5 Schematic of cross-section of a trickling filter. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

18.9.2 Trickling Filters

Trickling filters have been used to treat wastewater since the 1890s. It was found that if settled wastewater was passed over rock surfaces, slime grew on the rocks and the water became cleaner. Today we still use this principle, but in many installations we use plastic media instead of rocks.

In most wastewater treatment systems, the trickling filter follows primary treatment and includes a secondary settling tank or clarifier as shown in Figure 18.4. Trickling filters are widely used for the treatment of domestic and industrial wastes. The process is a fixed film biological treatment method designed to remove BOD and suspended solids.

A trickling filter consists of a rotating distribution arm that sprays and evenly distributes liquid wastewater over a circular bed of fist-sized rocks, other coarse materials, or synthetic media (see Figure 18.5). The spaces between the media allow air to circulate easily so that aerobic conditions can be maintained. The spaces also allow wastewater to trickle down through, around, and over the media. A layer of biological slime that absorbs and consumes the wastes trickling through the bed covers the media material. The organisms aerobically decompose the solids and produce more organisms and stable wastes that either become part of the slime or are discharged back into the wastewater flowing over the media. This slime consists mainly of bacteria, but it may also include algae, protozoa, worms, snails, fungi, and insect larvae. The accumulating slime occasionally sloughs off (sloughings) individual media materials (see Figure 18.6) and is collected at the bottom of the filter, along with the treated wastewater, and passed on to the secondary settling tank where it is removed.

The overall performance of the trickling filter is dependent on hydraulic and organic loading, temperature, and recirculation.

18.9.2.1 Trickling Filter Definitions

To clearly understand the correct operation of the trickling filter, the operator must be familiar with certain terms. The following list of terms applies to the trickling filter process.

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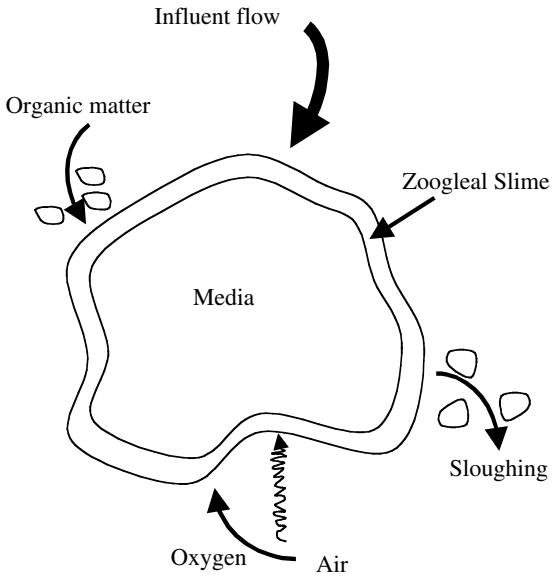

FIGURE 18.6 Filter media showing biological activities that take place on surface area. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

We assume that other terms related to other units within the treatment system (plant) are already familiar to operators:

Biological towers a type of trickling filter that is very deep (10 to 20 ft). Filled with a lightweight synthetic media, these towers are also know as oxidation or roughing towers or (because of their extremely high hydraulic loading) super-rate trickling filters.

Biomass the total mass of organisms attached to the media. Similar to solids inventory in the activated sludge process, it is sometimes referred to as the zoogleal slime.

Distribution arm the device most widely used to apply wastewater evenly over the entire surface of the media. In most cases, the force of the wastewater being sprayed through the orifices moves the arm.

Filter underdrain the open space provided under the media to collect the liquid (wastewater and sloughings) and to allow air to enter the filter. It has a sloped floor to collect the flow to a central channel for removal.

Hydraulic loading the amount of wastewater flow applied to the surface of the trickling filter media. It can be expressed in several ways: flow per square foot of surface per day, flow per acre per day, or flow per acre-foot per day. The hydraulic loading includes all flow entering the filter.

High-rate trickling filters a classification (see Table 18.4) in which the organic loading is in the range of 25 to 100 lb BOD/1000 ft^3 of media/d. The standard rate filter may also produce a highly nitrified effluent.

Media an inert substance placed in the filter to provide a surface for the microorganism to grow on. The media can be field stone, crushed stone, slag, plastic, or redwood slats.

Organic loading the amount of BOD or COD applied to a given volume of filter media. It does not include the BOD or COD contributed to any recirculated flow and is commonly expressed as pounds of BOD or COD per 1000 ft^3 of media.

Recirculation the return of filter effluent back to the head of the trickling filter. It can level flow

TABLE 18.4
Trickling Filter Classification

Filter Class	Standard	Intermediate	High Rate	Super High Rate	Roughing
Hydraulic Loading (gal/d/ft^2)	25–90	90–230	230–900	350–2100	>900
Organic Loading BOD/1000 ft^3	5–25	15–30	25–300	Up to 300	>300
Sloughing frequency	Seasonal	Varies	Continuous	Continuous	Continuous
Distribution	Rotary	Rotary fixed	Rotary fixed	Rotary	Rotary Fixed
Recirculation	No	Usually	Always	Usually	Not usually
Media depth (ft)	6–8	6–8	3–8	Up to 40	3–20
Media type	Rock	Rock	Rock	Plastic	Rock
	Plastic	Plastic	Plastic		Plastic
	Wood	Wood	Wood		Wood
Nitrification	Yes	Some	Some	Limited	None
Filter flies	Yes	Variable	Variable	Very few	Not usually
BOD removal	80–85%	50–70%	65–80%	65–85%	40–65%
TSS removal	80–85%	50–70%	65–80%	65–85%	40–65%

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

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variations and assist in solving operational problems such as ponding, filter flies, and odors.

Roughing filters a classification of trickling filters (see Table 18.4) in which the organic is in excess of 200 lb BOD/1000 ft^3 of media/d. A roughing filter is used to reduce the loading on other biological treatment processes to produce an industrial discharge that can be safely treated in a municipal treatment facility.

Sloughing the process in which the excess growths break away from the media and wash through the filter to the underdrains with the wastewater. These sloughings must be removed from the flow by settling.

Staging the practice of operating two or more trickling filters in series. The effluent of one filter is used as the influent of the next. This practice can produce a higher quality effluent by removing additional BOD or COD.

18.9.2.2 Trickling Filter Equipment

The trickling filter distribution system is designed to spread wastewater evenly over the surface of the entire media. The most common system is the rotary distributor, which moves above the surface of the media and sprays the wastewater on the surface. The force of the water leaving the orifices drives the rotary system. The distributor arms usually have small plates below each orifice to spread the wastewater into a fan-shaped distribution system. The second type of distributor is the fixed nozzle system. In this system, the nozzles are fixed in place above the media and are designed to spray the wastewater over a fixed portion of the media. This system is used frequently with deep bed synthetic media filters.

Note: Trickling filters that use ordinary rock are normally only about 3 m in depth because of structural problems caused by the weight of rocks, which also requires the construction of beds that are quite wide (in many applications, up to 60 ft in diameter). When synthetic media is used, the bed can be much deeper.

No matter which type of media is selected, the primary consideration is that it must be capable of providing the desired film location for the development of the biomass. Depending on the type of media used and the filter classification, the media may be 3 to 20 or more ft in depth.

The underdrains are designed to support the media, collect the wastewater and sloughings and carry them out of the filter, and provide ventilation to the filter.

Note: In order to ensure sufficient airflow to the filter, the underdrains should never be allowed to flow more than 50% full of wastewater.

The effluent channel is designed to carry the flow from the trickling filter to the secondary settling tank.

The secondary settling tank provides 2 to 4 h of detention time to separate the sloughing materials from the treated wastewater. Design, construction, and operation are similar to the primary settling tank's. Longer detention times are provided because the sloughing materials are lighter and settle more slowly.

Recirculation pumps and piping are designed to recirculate (and thus improve the performance of the trickling filter or settling tank) a portion of the effluent back to be mixed with the filter influent. When recirculation is used, pumps and metering devices must be provided.

18.9.2.3 Filter Classifications

Trickling filters are classified by hydraulic and organic loading. The expected performance and the construction of the trickling filter are also determined by the filter classification. Filter classifications include: standard rate, intermediate rate, high rate, super high rate (plastic media), and roughing rate types. Standard rate, high rate, and roughing rate are the filter types most commonly used.

The standard rate filter has a hydraulic loading of 25 to 90 gal/d/ft^3 and a seasonal sloughing frequency. It does not employ recirculation and typically has a 80–85% BOD removal rate and 80 to 85% TSS removal rate.

The high rate filter has a hydraulic loading of 230 to 900 gal/d/ft^3 and a continuous sloughing frequency. It always employs recirculation and typically has a 65 to 80% BOD removal rate and 65 to 80% TSS removal rate.

The roughing filter has a hydraulic loading of >900 gal/d/ft^3 and a continuous sloughing frequency. It does not normally include recirculation and typically has a 40 to 65% BOD removal rate and 40 to 65% TSS removal rate.

18.9.2.4 Standard Operating Procedures

Standard operating procedures for trickling filters include sampling and testing, observation, recirculation, maintenance, and expectations of performance.

Collection of influent and process effluent samples to determine performance and monitor process condition of trickling filters is required. DO, pH, and settleable solids testing should be collected daily. BOD and suspended solids testing should be done as often as practical to determine the per cent removal.

The operation and condition of the filter should be observed daily. Items to observe include the distributor movement, uniformity of distribution, evidence of operation or mechanical problems, and the presence of objectionable odors. In addition to the items above the normal observation for a settling tank should also be performed.

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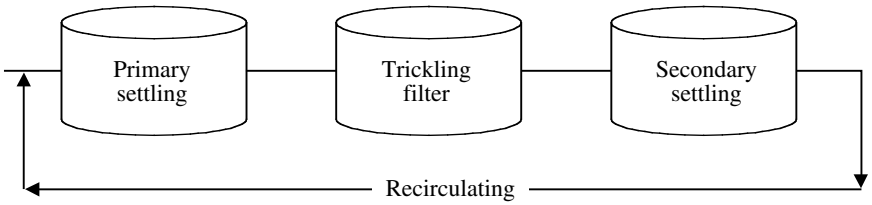

FIGURE 18.7 Common form of recirculation. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

Recirculation is used to reduce organic loading, improve sloughing, reduce odors, and reduce or eliminate filter fly or ponding problems. The amount of recirculation is dependent on the design of the treatment plant and the operational requirements of the process. Recirculation flow may be expressed as a specific flow rate (i.e., 2.0 MGD). In most cases, it is expressed as a ratio (e.g., 3:1, 0.5:1.0, etc). The recirculation is always listed as the first number and the influent flow listed as the second number.

Note: Since the second number in the ratio is always 1.0, the ratio is sometimes written as a single number (dropping the 1.0)

Flows can be recirculated from various points following the filter to various points before the filter. The most common form of recirculation removes flow from the filter effluent or settling tank and returns it to the influent of the trickling filter as shown in Figure 18.7.

Maintenance requirements include lubrication of mechanical equipment, removal of debris from the surface and orifices, as well as adjustment of flow patterns and maintenance associated with the settling tank.

Expected performance ranges for each classification of trickling filter. The levels of BOD and suspended solids removal are also dependent on the type of filter.

18.9.2.5 General Process Description

The trickling filter process involves spraying wastewater over a solid media such as rock, plastic, or redwood slats (or laths). As the wastewater trickles over the surface of the media, a growth of microorganisms (bacteria, protozoa, fungi, algae, helminthes or worms, and larvae) develops. This growth is visible as a shiny slime very similar to the slime found on rocks in a stream. As the wastewater passes over this slime, the slime adsorbs the organic (food) matter. This organic matter is used for food by the microorganisms. At the same time, air moving through the open spaces in the filter transfers oxygen to the wastewater. This oxygen is then transferred to the slime to keep the outer layer aerobic. As the microorganisms use the food and oxygen, they produce more organisms, carbon dioxide, sulfates, nitrates, and other stable by-products; these materials are then discarded from the slime back into the wastewater flow and are carried out of the filter. The process is shown in the following equation:

$$\text{Organics} + \text{Organisms} + O_2 = \text{More Organisms} + CO_2 + \text{Solid Wastes} \tag{18.23}$$

The growth of the microorganisms and the buildup of solid wastes in the slime make it thicker and heavier. When this slime becomes too thick, the wastewater flow breaks off parts of the slime. These must be removed in the final settling tank.

In some trickling filters, a portion of the filter effluent is returned to the head of the trickling filter to level out variations in flow and improves operations (recirculation).

18.9.2.5.1 Overview and Brief Summary of Trickling Filter Process

The following list provides an overview of the trickling filter process:

1. A trickling filter consists of a bed of coarse media, usually rocks or plastic, covered with microorganisms.
2. The wastewater is applied to the media at a controlled rate, using a rotating distributor arm or fixed nozzles. Organic material is removed by contact with the microorganisms as the wastewater trickles down through the media openings. The treated wastewater is collected by an underdrain system.
3. The trickling filter is usually built into a tank that contains the media. The filter may be square, rectangular, or circular.
4. The trickling filter does not provide any actual filtration. The filter media provides a large amount of surface area that the microorganisms can cling to and grow in a slime that forms on the media as they feed on the organic material in the wastewater.
5. The slime growth on the trickling filter media periodically sloughs off and is settled and removed in a secondary clarifier that follows the filter.
6. Key factors in trickling filter operation include the following concepts:

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A. Hydraulic loading rate

$$\text{Hydraulic Loading Rate } \left(\text{gal/d/ft}^2\right) = \frac{\text{Q (gal/d) (including recirculation)}}{\text{Media Top Surface } \left(\text{ft}^2\right)}$$

B. Organic loading rate

$$\text{Organic Loading Rate } \left(\text{lb/d/1000 ft}^3\right) = \frac{\text{BOD in Filter (lb/d)}}{\text{Media Volume } \left(1000 \text{ ft}^3\right)}$$

C. Recirculation

$$\text{Recirculation (ratio)} = \frac{\text{Recirculation Flow (MGD)}}{\text{Average Influent Flow (MGD)}}$$

18.9.2.6 Operator Observations, Process Problems, and Troubleshooting

Trickling filter operation requires routine observation, meter readings, process control sampling and testing, and process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems and appropriate corrective actions.

18.9.2.6.1 Operator Observations

1. Slime — The operator checks the thickness of slime to ensure that it is thin and uniform (normal) or thick and heavy (indicates organic overload). The operator is concerned with ensuring that excessive recirculation is not taking place and checks slime toxicity (if any). The operator is also concerned about the color of the slime. Green slime is normal, dark green or black slime indicates organic overload. Other colors may indicate industrial waste or chemical additive contamination. The operator should check the subsurface growth of the slime to ensure that it is normal (thin and translucent). If growth is thick and dark, organic overload conditions are indicated. Distribution arm operation is a system function important to slime formation. It must be checked regularly for proper operation. For example, the distribution of slime should be even and uniform. Striped conditions indicate clogged orifices or nozzles.
2. Flow — Flow distribution must be checked to ensure uniformity. If nonuniform, the arms are not level or the orifices are plugged. Flow drainage is also important. Drainage should be uniform and rapid. If not, ponding may occur from media breakdown or debris on surface.
3. Distributor — Movement of the distributor is critical to proper operation of the trickling filter. Movement should be uniform and smooth. Chattering, noisy operation may indicate bearing failure. The distributor seal must be checked to ensure there is no leakage.
4. Recirculation — The operator must check the rate of recirculation to ensure that it is within design specifications. Rates above design specifications indicate hydraulic overloading, while rates under design specifications indicate hydraulic underloading.
5. Media — The operator should check to ensure that media are uniform.

18.9.2.6.2 Process Control Sampling and Testing

To ensure proper operation of the trickling filter, sampling and scheduling are important. For samples and the tests derived from the samples to be beneficial, operators must perform a variety of daily or variable tests. Individual tests and sampling may be needed daily, weekly, or monthly, depending on seasonal change. Frequency may be lower during normal operations and higher during abnormal conditions.

The information gathered through collection and analysis of samples from various points in the trickling filter process is helpful in determining the current status of the process as well as identifying and correcting operational problems.

The following routine sampling points and types of tests will permit the operator to identify normal and abnormal operating conditions.

1. Filter influent — Tests include DO, pH, temperature, settleable solids, BOD, suspended solids, and metals.
2. Recirculated flow — Tests include DO, pH, flow rate, and temperature.
3. Filter effluent — Tests include DO, pH, and jar tests.
4. Process effluent — Tests include DO, pH, settleable solids, BOD, and suspended solids.

18.9.2.6.3 Troubleshooting Operational Problems

(Note: Much of the information in this section is based on the Environmental Protection Agency's (EPA) *Performance Evaluation and Troubleshooting at Municipal*

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Wastewater Treatment Facilities, Washington, D.C., current editions.)

The following sections are not all-inclusive; they do not cover all of the operational problems associated with the trickling filter process. They do provide information on the most common operational problems.

18.9.2.6.3.1 Ponding

1. Symptoms
   A. Small pools or puddles of water on the surface of the media.
   B. Decreased performance in the removal of BOD and TSS.
   C. Possible odors due to anaerobic conditions in the media.
   D. Poor air flow through the media.
2. Causal factors
   A. Inadequate hydraulic loading to keep the media voids flushed clear.
   B. Application of high strength wastes without sufficient recirculation to provide dilution.
   C. Nonuniform media.
   D. Degradation of the media due to aging or weathering
   E. Medium is uniform, but is too small.
   F. Debris (moss, leaves, sticks) or living organisms (snails) clog the void spaces.
3. Corrective actions
   Corrective actions are listed in increasing impact on the quality of the plant effluent:
   A. Remove all leaves, sticks, and other debris from the media.
   B. Increase recirculation of dilute, high-strength wastes to improve sloughing to keep voids open.
   C. Use high-pressure stream of water to agitate and flush the ponded area.
   D. Rake or fork the ponded area.
   E. Dose the filter with chlorine solution for 2 to 4 h. The specific dose of chlorine required will depend on the severity of the ponding problem. When using elemental chlorine, the dose must be sufficient to provide a residual at the orifices of 1–50 mg/L. If the filter is severely clogged, the higher residuals may be needed to unload the majority of the biomass. If the filter cannot be dosed by elemental chlorine, chlorinated lime or high test hypochlorite powder may be used. Dosing should be in the range of 8 to 10 lb of chlorine/1000 ft^2 of media.
   F. If the filter design permits, the filter media can be flooded for a period of 4 h. Remember, if the filter is flooded, care must be taken to prevent hydraulic overloads of the final settling tank. The trickling filter should be drained slowly at low flow periods.
   G. Dry the media. By stopping the flow to the filter, the slime will dry and loosen. When the flow is restarted, the loosened slime will flow out of the filter. The amount of drying time will be dependent on the thickness of the slime and the amount of removal desired. Time may range from a few hours to several days.

Note: Portions of the media can be dried without taking the filter out of service by plugging the orifices that normally service the area.

Note: If these corrective actions do not provide the desired improvement, the media must be carefully inspected. Remove a sample of the media from the affected area. Carefully clean it, inspect for its solidity, and determine its size uniformity (3 to 5 in.). If it is acceptable, the media must be carefully replaced. If the media appear to be decomposing or are not uniform, then they should be replaced.

18.9.2.6.3.2 Odors

Frequent offensive odors usually indicate an operational problem. These foul odors occur within the filter periodically and are normally associated with anaerobic conditions. Under normal circumstances, a slight anaerobic slime layer forms due to the inability of oxygen to penetrate all the way to the media. Under normal operation, the outer slime layers will remain aerobic, and no offensive odors are produced.

1. Causal factors
   A. Excessive organic loading due to poor filter effluent quality (recirculation), poor primary treatment operation, and poor control of sludge treatment process that results in high BOD recycle flows.
   B. Poor ventilation because of submerged or obstructed underdrains, clogged vent pipes, or clogged void spaces.
   C. Filter is overloaded hydraulically or organically.
   D. Poor housekeeping.
2. Corrective actions
   A. Evaluate the operation of the primary treatment process. Eliminate any short-circuiting. Determine any other actions that can be taken to improve the performance of the primary process.

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B. Evaluate and adjust control of sludge treatment processes to reduce the BOD or recycle flows.
C. Increase recirculation rate to add additional DO to filter influent. Do not increase recirculation rate if the flow rate through the underdrains would cause less than 50% open space.
D. Maintain aerobic conditions in filter influent.
E. Remove debris from media surface.
F. Flush underdrains and vent pipes.
G. Add one of the commercially available masking agents to reduce odors and prevent complaints.
H. Add chlorine at a 1 to 2 mg/L residual for several hours at low flow. This will reduce activity and cut down on the oxygen demand. Chlorination only treats symptoms; a permanent solution must be determined and instituted.

18.9.2.6.3.3 High Clarifier Effluent Suspended Solids and BOD

1. Symptom
   A. The effluent from the trickling filter process-settling unit contains a high concentration of suspended solids.
2. Causal factors
   A. Recirculated flows are too high, causing hydraulic overloading of the settling tank. In multiple unit operations, the flow is not evenly distributed.
   B. Settling tank baffles or skirts have corroded or broken.
   C. Sludge collection mechanism is broken or malfunctioning.
   D. Effluent weirs are not level.
   E. Short-circuiting occurs because of temperature variations.
   F. Improper sludge withdrawal rate or frequency.
   G. Excessive solids loading from excessive sloughing.
3. Corrective actions
   A. Check hydraulic loading and adjust recirculated flow if hydraulic loading is too high.
   B. Adjust flow to ensure equal distribution.
   C. Inspect sludge removal equipment. Repair broken equipment.
   D. Monitor sludge blanket depth and sludge solids concentration; adjust withdrawal rate and/or frequency to maintain aerobic conditions in settling tank.
   E. Adjust effluent weir to obtain equal flow over all parts of the weir length.
   F. Determine temperature in the clarifier at various points and depths throughout the clarifier. If depth temperatures are consistently 1 to 2°F lower than surface readings, a temperature problem exists. Baffles may be installed to help to break up these currents.
   G. High sloughing rates because of the biological activity or temperature changes may create excessive solids loading. An addition of 1 to 2 mg/L of cationic polymer may be helpful in improving solids capture. Remember, if polymer addition is used, solids withdrawal must be increased.
   H. High sloughings because of organic overloading, toxic wastes, or wide variations in influent flow are best controlled at their source.

18.9.2.6.3.4 Filter Flies

1. Symptoms
   A. The trickling filter and surrounding area become populated with large numbers of very small flying insects (psychoda moths).
2. Causal factors
   A. Poor housekeeping.
   B. Insufficient recirculation.
   C. Intermittent wet and dry conditions.
   D. Warm weather.
3. Corrective actions
   Corrective actions for filter fly problems revolve around the need to disrupt the fly's life cycle (7 to 10 d in warm weather):
   A. Increase recirculation rate to obtain a hydraulic loading of at least 200 gal/d/ft^2. At this rate, filter fly larvae are normally flushed out of the filter.
   B. Clean filter walls and remove weeds, brush, and shrubbery around the filter. This removes some of the area for fly breeding.
   C. Dose the filter periodically with low chlorine concentrations (less than 1 mg/L). This normally destroys larvae.
   D. Dry the filter media for several hours.
   F. Flood the filter for 24 h.
   G. Spray area around the filter with insecticide. Do not use insecticide directly on the media, because of the chance of carryover and unknown effects on the slime populations.

18.9.2.6.3.5 Freezing

1. Symptoms
   A. Decreased air temperature results in visible ice formation and decreased performance.
   B. Distributed wastes are in a thin film or spray. This is more likely to cause ice formation.

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2. Causal factors
   A. Recirculation causes increased temperature drops and losses.
   B. Strong prevailing winds cause heat losses.
   C. Intermittent dosing allows water to stand too long, causing freezing.
3. Corrective actions
   All corrective actions are based upon a need to reduce heat loss as the wastes move through the filter.
   A. Reduce recirculation as much as possible to minimize cooling effects.
   B. Operate two stage filters in parallel to reduce heat loss.
   C. Adjust splash plates and orifices to obtain a coarse spray.
   D. Construct a windbreak or plant evergreens or shrubs in the direction of the prevailing wind.
   E. If intermittent dosing is used, leave dump gates open.
   F. Cover pump wet wells and dose tanks to reduce heat losses.
   G. Cover filter media to reduce heat loss.
   H. Remove ice before it becomes large enough to cause stoppage of arms.

Note: During periods of cold weather, the filter will show decreased performance. However, the filter should not be shut off for extended periods. Freezing of the moisture trapped within the media causes expansion and may cause structural damage.

18.9.2.7 Process Calculations

Several calculations are useful in the operation of a trickling filter, these include: total flow, hydraulic loading, and organic loading.

18.9.2.7.1 Total Flow

If the recirculated flow rate is given, total flow is:

$$\text{Total Flow (MGD)} = \text{Influent Flow (MGD)} + \text{Recirculation Flow (MGD)}$$

$$\text{Total Flow (gal/d)} = \text{Total Flow (MGD)} \times 1{,}000{,}000 \text{ gal/MG} \tag{18.24}$$

Note: The total flow to the tricking filter includes the influent flow and the recirculated flow. This can be determined using the recirculation ratio:

$$\text{Total Flow (MGD)} = \text{Influent Flow} \times (\text{Recirculation Rate} + 1.0)$$

EXAMPLE 18.31

Problem:

The trickling filter is currently operating with a recirculation rate of 1.5. What is the total flow applied to the filter when the influent flow rate is 3.65 MGD?

Solution:

$$\text{Total Flow (MGD)} = 3.65 \text{ MGD} \times (1.5 + 1.0) = 9.13 \text{ MGD}$$

18.9.2.7.2 Hydraulic Loading

Calculating the hydraulic loading rate is important in accounting for both the primary effluent as well as the recirculated trickling filter effluent. Both of these are combined before being applied to the surface of the filter. The hydraulic loading rate is calculated based on the surface area of the filter.

EXAMPLE 18.32

Problem:

A trickling filter 90-ft in diameter is operated with a primary effluent of 0.488 MGD and a recirculated effluent flow rate of 0.566 MGD. Calculate the hydraulic loading rate on the filter in units gallons per day per square foot.

Solution:

The primary effluent and recirculated trickling filter effluent are applied together across the surface of the filter, therefore:

$$0.488 \text{ MGD} + 0.566 \text{ MGD} = 1.054 \text{ MGD} = 1{,}054{,}000 \text{ gal/d}$$

$$\text{Circular Surface Area} = 0.785 \times (\text{Diameter})^2 = 0.785 \times (90 \text{ ft})^2 = 6359 \text{ ft}^2$$

$$\frac{1{,}054{,}000 \text{ gal/d}}{6359 \text{ ft}^2} = 165.7 \text{ gal/d/ft}^2$$

18.9.2.7.3 Organic Loading Rate

As mentioned earlier, trickling filters are sometimes classified by the organic loading rate applied. The organic

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loading rate is expressed as a certain amount of BOD applied to a certain volume of media.

EXAMPLE 18.33

Problem:

A trickling filter, 50 ft in diameter, receives a primary effluent flow rate of 0.445 MGD. Calculate the organic loading rate in units of pounds of BOD applied per day per 900 ft^3 of media volume. The primary effluent BOD concentration is 85 mg/L. The media depth is 9 ft.

Solution:

$$0.445\ \text{MGD} \times 85\ \text{mg/L} \times 8.34\ \text{lb/gal} = 315.5\ \text{BOD applied/d}$$

$$\text{Surface Area} = 0.785 \times (\text{Diameter})^2 = 0.785 \times (50\ \text{ft})^2 = 1962.5\ \text{ft}^2$$

$$A \times D = v$$

$$1962.5\ \text{ft}^2 \times 9\ \text{ft}^2 = 17{,}662.5\ (\text{Trickling filter volume})$$

To determine the pounds of BOD/1000 ft^3 in a volume of thousands of cubic feet, we must set up the equation as shown below:

$$\frac{315.5\ \text{BOD/d}}{17{,}662.5} \times \frac{1000}{1000}$$

Regrouping the numbers and the units together:

$$= \frac{315.5\ \text{lb} \times 1000}{17{,}662.5} \times \frac{\text{lb BOD/d}}{1000\ \text{ft}^3}$$

$$= 17.9\ \text{lb BOD/d/1000 ft}^3$$

18.9.2.7.4 Settling Tanks

In the operation of settling tanks that follow trickling filters, various calculations are routinely made to determine detention time, surface settling rate, hydraulic loading and sludge pumping.

18.9.3 ROTATING BIOLOGICAL CONTACTORS

The RBC is a biological treatment system (see Figure 18.8) and is a variation of the attached growth idea provided by the trickling filter. Still relying on microorganisms that grow on the surface of a medium, the RBC is a fixed film biological treatment device; the basic biological process

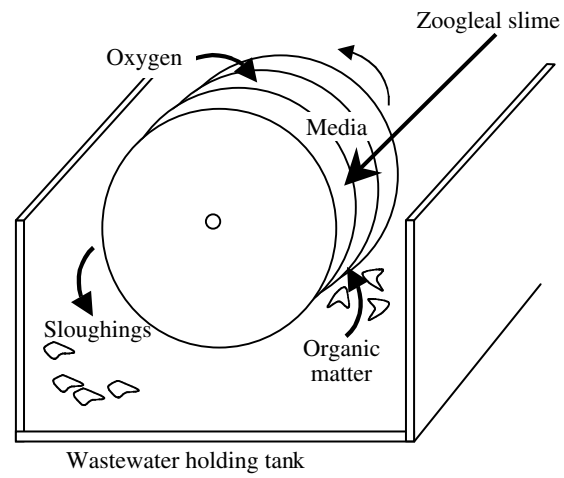

FIGURE 18.8 Cross-section of a rotating biological contactor (RBC) treatment system. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

is similar to that occurring in the trickling filter. An RBC consists of a series of closely spaced (mounted side by side), circular, plastic (synthetic) disks that are typically about 3.5 m in diameter and attached to a rotating horizontal shaft (see Figure 18.8). Approximately 40% of each disk is submersed in a tank containing the wastewater to be treated. As the RBC rotates, the attached biomass film (zoogleal slime) that grows on the surface of the disk moves into and out of the wastewater. While submerged in the wastewater, the microorganisms absorb organics; while they are rotated out of the wastewater, they are supplied with needed oxygen for aerobic decomposition. As the zoogleal slime reenters the wastewater, excess solids and waste products are stripped off the media as sloughings. These sloughings are transported with the wastewater flow to a settling tank for removal.

Modular RBC units are placed in series (see Figure 18.9) simply because a single contactor is not sufficient to achieve the desired level of treatment; the resulting treatment achieved exceeds conventional secondary treatment. Each individual contactor is called a stage and the group is known as a train. Most RBC systems consist of two or more trains with three or more stages in each. The key advantage in using RBCs instead of trickling filters is that RBCs are easier to operate under varying load conditions, since it is easier to keep the solid medium wet at all times. The level of nitrification, which can be achieved by a RBC system, is also significant. This is especially the case when multiple stages are employed.

18.9.3.1 RBC Equipment

The equipment that makes up a RBC includes the rotating biological contactor (the media: either standard or high

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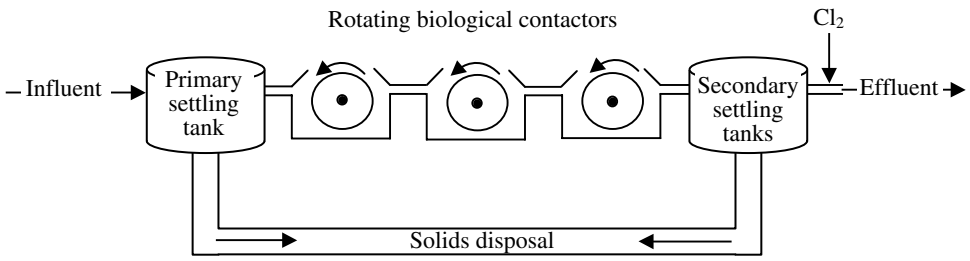

FIGURE 18.9 Rotating biological contactor (RBC) treatment system in series. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

density), a center shaft, drive system, tank, baffles, housing or cover, and a settling tank.

The rotating biological contactor consists of circular sheets of synthetic material (usually plastic) that are mounted side by side on a shaft. The sheets (media) contain large amounts of surface area for growth of the biomass.

The center shaft provides the support for the disks of media and must be strong enough to support the weight of the media and the biomass. Experience has indicated a major problem has been the collapse of the support shaft.

The drive system provides the motive force to rotate the disks and shaft. The drive system may be mechanical, air driven, or a combination of each. When the drive system does not provide uniform movement of the RBC, major operational problems can arise.

The tank holds the wastewater where the RBC rotates. It should be large enough to permit variation of the liquid depth and detention time.

Baffles are required to permit proper adjustment of the loading applied to each stage of the RBC process. Adjustment can be made to increase or decrease the submergence of the RBC.

RBC stages are normally enclosed in some type of protective structure (cover) to prevent loss of biomass due to severe weather changes (snow, rain, temperature, wind, sunlight, etc.). In many instances this housing greatly restricts access to the RBC.

The settling tank is provided to remove the sloughing material created by the biological activity and is similar in design to the primary settling tank. The settling tank provides 2- to 4-h detention times to permit settling of lighter biological solids.

18.9.3.2 RBC Operation

During normal operation, operator vigilance is required to observe the RBC movement, slime color, and appearance. If the unit is covered, observations may be limited to that portion of the media, which can be viewed through the access door.

Sampling and testing should be conducted daily for DO content and pH. BOD and suspended solids testing should also be accomplished to aid in assessing performance.

18.9.3.3 RBC: Expected Performance

The RBC normally produces a high quality effluent with BOD at 85 to 95% and suspended solids removal at 85 to 95%. The RBC treatment process may also significantly reduce (if designed for this purpose) the levels of organic nitrogen and ammonia nitrogen.

18.9.3.4 Operator Observations, Process Problems, and Troubleshooting

Rotating biological filter operation requires routine observation, process control sampling and testing, troubleshooting, and process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems and appropriate corrective actions.

18.9.3.4.1 Operator Observations

Note: If the RBC is covered, observations may be limited to the portion of the media that can be viewed through the access door.

1. Rotation — The operator routinely checks the operation of the RBC to ensure that smooth, uniform rotation is occurring (normal operation). Erratic, nonuniform rotation indicates a mechanical problem or uneven slime growth. If no movement is observed, mechanical problems or extreme excess of slime growth are indicated.
2. Slime color and appearance — Slime color and appearance can indicate process condition. Gray, shaggy slime growth on the RBC indicates normal operation. Reddish brown or golden brown shaggy growth indicates normal during nitrification. A very dark brown, shaggy growth (with worms present) indicates a very old slime. White chalky growth indicates high influent sulfur or sulfide levels. No visible slime growth to the RBC indicates a severe pH or temperature change.

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18.9.3.4.2 Process Control Sampling and Testing

For process control, the RBC process does not require large amounts of sampling and testing to provide the information required. The frequency for performing suggested testing depends on available resources and variability of process. Frequency may be lower during normal operation and higher during abnormal conditions.

The following routine sampling points and types of tests will permit the operator to identify normal and abnormal operating conditions:

1. RBC train influent — Tests include pH, temperature, settleable solids, BOD, suspended solids, and metals.
2. RBC — Test includes speed of rotation.
3. RBC train effluent — Tests include DO, pH, jar tests.
4. Process effluent — Tests include DO, pH, settleable solids, BOD, and suspended solids

18.9.3.4.3 Troubleshooting Operational Problems

(Note: Much of the information in this section is based on material provided by EPA in *Performance Evaluation and Troubleshooting at Municipal Wastewater Treatment Facilities*, Washington, D.C., current edition.)

The following sections are not all-inclusive; they do not cover all of the operational problems associated with the rotating biological contactor process. They do provide information on the most common operational problems.

18.9.3.4.3.1 White Slime

1. Symptom
   A. White slime on most of the disk area.
2. Causal factors
   A. High hydrogen sulfide in influent
   B. Septic influent
   C. First stage overloaded
3. Corrective actions
   A. Aerate RBC or plant influent.
   B. Add sodium nitrate or hydrogen peroxide to influent.
   C. Adjust baffles between stages 1 and 2 to increase fraction of total surface area in first stage.

18.9.3.4.3.2 Excessive Sloughing

1. Symptom
   A. Loss of slime.
2. Causal factors
   A. Excessive pH variance.
   B. Toxic influent.
3. Corrective actions
   A. Implement and enforce pretreatment program.
   B. Install pH control equipment.
   C. Equalize flow to acclimate organisms.

18.9.3.4.3.3 RBC Rotation

1. Symptom
   A. RBC rotation is uneven.
2. Causal factors
   A. Mechanical growth.
   B. Uneven growth.
3. Corrective actions
   A. Repair mechanical problem.
   B. Increase rotational speed.
   C. Adjust baffles to decrease loading.
   D. Increase sloughing.

18.9.3.4.3.4 Solids

1. Symptom
   A. Solids accumulating in reactors.
2. Causal factors
   A. Inadequate pretreatment.
3. Corrective actions
   A. Identify and correct grit removal problem.
   B. Identify and correct primary settling problem.

18.9.3.4.3.5 Shaft Bearings

1. Symptom
   A. Shaft bearings running hot or failing.
2. Causal factor
   A. Inadequate maintenance.
3. Corrective action
   A. Follow manufacturer's recommendations.

18.9.3.4.3.6 Drive Motor

1. Symptom
   A. Drive motor running hot.
2. Causal factors
   A. Inadequate maintenance.
   B. Improper chain drive alignment.
3. Corrective actions
   A. Follow manufacturer's recommendations.
   B. Adjust alignment.

18.9.3.5 RBC: Process Control Calculations

Several process control calculations may be useful in the operation of a RBC. These include soluble BOD, total media area, organic loading rate, and hydraulic loading rate. Settling tank calculations and sludge pumping calculations may be helpful for evaluation and control of the settling tank following the RBC.

18.9.3.5.1 RBC: Soluble BOD

The soluble BOD concentration of the RBC influent can be determined experimentally in the laboratory or it can be estimated using the suspended solids concentration and the K factor. The K factor is used to approximate the BOD (particulate BOD) contributed by the suspended matter. The K factor must be provided or determined experimentally

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in the laboratory. The K factor for domestic wastes normally ranges from 0.5 to 0.7.

$$\text{Soluble BOD}_5 = \text{Total BOD}_5 - (\text{K Factor} \times \text{Total Suspended Solids}) \tag{18.25}$$

EXAMPLE 18.34

Problem:

The suspended solids concentration of a wastewater is 250 mg/L. If the normal K value at the plant is 0.6, what is the estimated particulate BOD concentration of the wastewater?

Solution:

The K value of 0.6 indicates that about 60% of the suspended solids are organic suspended solids (particulate BOD):

$$250\ \text{mg/L} \times 0.6 = 150\ \text{mg/L particulate BOD}$$

EXAMPLE 18.35

Problem:

An RBC receives a flow of 2.2 MGD with a BOD content of 170 mg/L and suspended solids concentration of 140 mg/L. If the K value is 0.7, how many pounds of soluble BOD enter the RBC daily?

Solution:

$$\text{Total BOD} = \text{Particulate BOD} + \text{Soluble BOD}$$

$$170\ \text{mg/L} = 140\ \text{mg/L} \times 0.7 + x\ \text{mg/L}$$

$$170\ \text{mg/L} = 98\ \text{mg/L} + x\ \text{mg/L}$$

$$170\ \text{mg/L} - 98\ \text{mg/L} = x$$

$$x = 72\ \text{mg/L soluble BOD}$$

Now the pounds per day of soluble BOD may be determined:

$$\text{mg/L soluble BOD} \times \text{MGD Flow} \times 8.34\ \text{lb/gal} = \text{lb/d soluble BOD}$$

$$72\ \text{mg/L} \times 2.2\ \text{MGD} \times 8.34\ \text{lb/gal} = 1321\ \text{lb/d}$$

18.9.3.5.2 RBC: Total Media Area

Several process control calculations for the RBC use the total surface area of all the stages within the train. As was the case with the soluble BOD calculation, plant design information or information supplied by the unit manufacturer must provide the individual stage areas (or the total train area) because physical determination of this would be extremely difficult.

$$\text{Total Area} = \text{1st Sage Area} + \text{2nd Stage Area} + \ldots + n\text{th Stage Area} \tag{18.26}$$

18.9.3.5.3 RBC: Organic Loading Rate

If the soluble BOD concentration is known, the organic loading on a RBC can be determined. Organic loading on a RBC based on soluble BOD concentration can range from 3 to 4 lb/d/1000 ft^2.

EXAMPLE 18.36

Problem:

An RBC has a total media surface area of 102,500 ft^2 and receives a primary effluent flow rate of 0.269 MGD. If the soluble BOD concentration of the RBC influent is 159 mg/L, what is the organic loading rate in pounds per 1000 ft^2?

Solution:

$$0.269\ \text{MGD} \times 159\ \text{mg/L} \times \frac{8.34\ \text{lb}}{1\ \text{gal}} = 356.7\ \text{lb/d}$$

$$\frac{356.7\ \text{lb/d}}{102{,}500\ \text{ft}^2} \times \frac{1000(\text{number})}{1000(\text{unit})} = 3.48\ \text{lb/d/1000 ft}^2$$

18.9.3.5.4 RBC: Hydraulic Loading Rate

The manufacturer normally specifies the RBC media surface area and the hydraulic loading rate is based on the media surface area (usually in square feet). Hydraulic loading on a RBC can range from 1 to 3 gal/d/ft^2.

EXAMPLE 18.37

Problem:

An RBC treats a primary effluent flow rate of 0.233 MGD. What is the hydraulic loading rate in gal/d/ft^2 if the media surface area is 96,600 ft^2?

Solution:

$$\frac{233{,}000\ \text{gal/d}}{96{,}600\ \text{ft}^2} = 2.41\ \text{gal/d/ft}^2$$

18.10 ACTIVATED SLUDGE

The biological treatment systems discussed to this point (ponds, trickling filters, and RBCs) have been around for years. The trickling filter, for example, has been around and successfully used since the late 1800s. The problem

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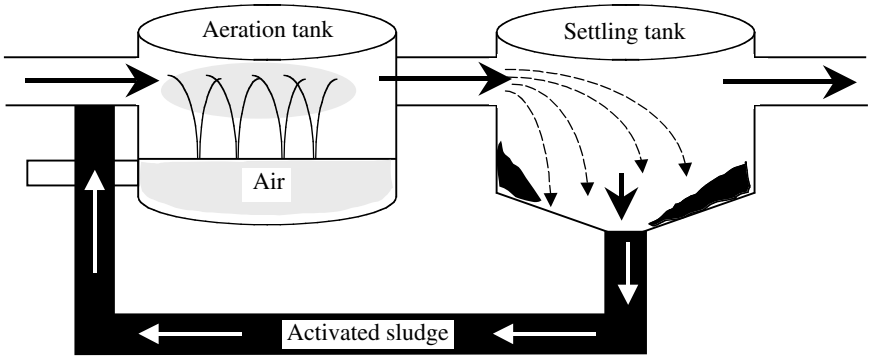

FIGURE 18.10 The activated sludge process. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

with ponds, trickling filters, and RBCs is that they are temperature sensitive and remove less BOD. In addition, trickling filters cost more to build than the activated sludge systems that were later developed.

Note: Although trickling filters and other systems cost more to build than activated sludge systems, it is important to point out that activated sludge systems cost more to operate because of the need for energy to run pumps and blowers.

As shown in Figure 18.10, the activated sludge process follows primary settling. The basic components of an activated sludge sewage treatment system include an aeration tank and a secondary basin, settling basin, or clarifier (see Figure 18.10). Primary effluent is mixed with settled solids recycled from the secondary clarifier and is then introduced into the aeration tank. Compressed air is injected continuously into the mixture through porous diffusers located at the bottom of the tank, usually along one side.

Wastewater is fed continuously into an aerated tank, where the microorganisms metabolize and biologically flocculate the organics. Microorganisms (activated sludge) are settled from the aerated mixed liquor under quiescent conditions in the final clarifier and are returned to the aeration tank. Left uncontrolled, the number of organisms would eventually become too great; therefore, some must periodically be removed (wasted). A portion of the concentrated solids from the bottom of the settling tank must be removed from the process (waste activated sludge). Clear supernatant from the final settling tank is the plant effluent.

18.10.1 Activated Sludge Terminology

To better understand the discussion of the activated sludge process presented in the following sections, you must understand the terms associated with the process. Some of these terms have been used and defined earlier in the text, but we list them here again to refresh your memory. Review these terms and remember them. They are used throughout the discussion.

Absorption taking in or reception of one substance into the body of another by molecular or chemical actions and distribution throughout the absorber.

Activated to speed up reaction. When applied to sludge, it means that many aerobic bacteria and other microorganisms are in the sludge particles.

Activated sludge a floc or solid formed by the microorganisms. It includes organisms, accumulated food materials, and waste products from the aerobic decomposition process.

Activated sludge process a biological wastewater treatment process in which a mixture or influent and activated sludge is agitated and aerated. The activated sludge is subsequently separated from the treated mixed liquor by sedimentation and is returned to the process as needed. The treated wastewater overflows the weir of the settling tank in which separation from the sludge takes place.

Adsorption the adherence of dissolved, colloidal, or finely divided solids to the surface of solid bodies when they are brought into contact.

Aeration mixing air and a liquid by one of the following methods: spraying the liquid in the air, diffusing air into the liquid, or agitating the liquid to promote surface adsorption of air.

Aerobic a condition in which free or dissolved oxygen is present in the aquatic environment. Aerobic organisms must be in the presence of DO to be active.

Bacteria single-cell plants that play a vital role in stabilization of organic waste.

Biochemical oxygen demand (BOD) a measure of the amount of food available to the microorganisms in a particular waste. It is measured by the amount of dissolved oxygen used up during a

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specific time period (usually 5 d, expressed as BOD_5).

Biodegradable from "degrade" (to wear away or break down chemically) and "bio" (by living organisms). Put it all together, and you have a substance, usually organic, that can be decomposed by biological action.

Bulking a problem in activated sludge plants that results in poor settleability of sludge particles.

Coning a condition that may be established in a sludge hopper during sludge withdrawal, when part of the sludge moves toward the outlet while the remainder tends to stay in place. Development of a cone or channel of moving liquids surrounded by relatively stationary sludge.

Decomposition generally, in waste treatment, decomposition refers to the changing of waste matter into simpler, more stable forms that will not harm the receiving stream.

Diffuser a porous plate or tube through which air is forced and divided into tiny bubbles for distribution in liquids. Commonly made of carborundum, aluminum, or silica sand.

Diffused air aeration a diffused air activated sludge plant takes air, compresses it, then discharges the air below the water surface to the aerator through some type of air diffusion device.

Dissolved oxygen (DO) atmospheric oxygen dissolved in water or wastewater.

Note: The typical required DO for a well-operated activated sludge plant is between 2.0 and 2.5 mg/L.

Facultative facultative bacteria can use either molecular (dissolved) oxygen or oxygen obtained from food materials. In other words, facultative bacteria can live under aerobic or anaerobic conditions.

Filamentous bacteria organisms that grow in thread or filamentous form.

Food-to-microorganisms ratio (F:M ratio) a process control calculation used to evaluate the amount of food (BOD or COD) available per pound of mixed liquor volatile suspended solids.

$$\frac{\text{Food}}{\text{Microorganism}} = \frac{\text{BOD lb/d}}{\text{MLVSS (lb)}}$$

$$= \frac{\text{Q (MGD)} \times \text{BOD (mg/L)} \times 8.34 \text{ lb/gal}}{\text{v (MG)} \times \text{MLVSS (mg/L)} \times 8.34 \text{ lb/gal}}$$

Fungi multicellular aerobic organisms.

Gould sludge age a process control calculation used to evaluate the amount of influent suspended solids available per pound of mixed liquor suspended solids.

Mean cell residence time (MCRT) the average length of time mixed liquor suspended solids particle remains in the activated sludge process. This is usually written as MCRT and may also be referred to as sludge retention rate.

$$\text{MCRT (d)} = \frac{\text{Solids in Activated Sludge Process (lb)}}{\text{Solids Removed from Process (lb/d)}}$$

Mixed liquor the contribution of return activated sludge and wastewater (either influent or effluent) that flows into the aeration tank.

Mixed liquor suspended solids (MLSS) the suspended solids concentration of the mixed liquor. Many references use this concentration to represent the amount of organisms in the liquor or the amount of organisms in the activated sludge process.

Mixed liquor volatile suspended solids (MLVSS) the organic matter in the mixed liquor suspended solids. This can also be used to represent the amount of organisms in the process.

Nematodes microscopic worms that may appear in biological waste treatment systems.

Nutrients substances required to support plant organisms. Major nutrients are carbon, hydrogen, oxygen, sulfur, nitrogen, and phosphorus.

Protozoa single-cell animals that are easily observed under the microscope at a magnification of 100×. Bacteria and algae are prime sources of food for advanced forms of protozoa.

Return activated sludge (RAS) the solids returned form the settling tank to the head of the aeration tank.

Rising sludge rising sludge occurs in the secondary clarifiers or activated sludge plant when the sludge settles to the bottom of the clarifier, is compacted, and then rises to the surface in relatively short time.

Rotifiers multicellular animals with flexible bodies and cilia near their mouths used to attract food. Bacteria and algae are their major source of food.

Secondary treatment a wastewater treatment process used to convert dissolved or suspended materials into a form that can be removed.

Settleability a process control test used to evaluate the settling characteristics of the activated sludge. Readings taken at 30 to 60 min are used to calculate the settled sludge volume and the sludge volume index.

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Settled sludge volume (SSV) the volume of milligrams per liter (or percent) occupied by an activated sludge sample after 30 or 60 minutes of settling. Normally written as SSV with a subscript to indicate the time of the reading used for calculation (SSV_{30} or SSV_{60}).

Shock load the arrival at a plant of a waste toxic to organisms in sufficient quantity or strength to cause operating problems, such as odor or sloughing off of the growth of slime on the trickling filter media. Organic overloads also can cause a shock load.

Sludge volume index (SVI) a process control calculation used to evaluate the settling quality of the activated sludge. Requires the SSV_{30} and mixed liquor suspended solids test results to calculate.

$$\text{Sludge Vol. Index (SVI), mL/g} = \frac{(\text{30 min settled vol., mL/L})(\text{1000 mg/g})}{\text{Mixed Liquor Suspended Solids, mg/L}}$$

Solids material in the solid state. The different types of solids include:

- **Dissolved** solids present in solution. Solids that will pass through a glass fiber filter.
- **Fixed** also known as the inorganic solids. The solids that are left after a sample is ignited at 550°C for 15 min.
- **Floatable solids** that will float to the surface of still water, sewage, or other liquid. Usually composed of grease particles, oils, light plastic material, etc. Also called scum.
- **Nonsettleable** finely divided suspended solids that will not sink to the bottom in still water, sewage, or other liquid in a reasonable period, usually 2 h. Non-settleable solids are also known as colloidal solids.
- **Suspended** solids that will not pass through a glass fiber filter.
- **Total** solids in water, sewage, or other liquids. It includes the suspended solids and dissolved solids.
- **Volatile** organic solids. Measured as the solids that are lost on ignition of the dry solids at 550°C.

Waste activated sludge (WAS) the solids being removed from the activated sludge process.

18.10.2 Activated Sludge Process: Equipment

The equipment requirements for the activated sludge process are more complex than other processes discussed. Equipment includes an aeration tank, aeration, system-settling tank, return sludge, and waste sludge.

18.10.2.1 Aeration Tank

The aeration tank is designed to provide the required detention time (depends on the specific modification) and ensure that the activated sludge and the influent wastewater are thoroughly mixed. Tank design normally attempts to ensure no dead spots are created.

18.10.2.2 Aeration

Aeration can be mechanical or diffused. Mechanical aeration systems use agitators or mixers to mix air and mixed liquor. Some systems use a sparge ring to release air directly into the mixer. Diffused aeration systems use pressurized air released through diffusers near the bottom of the tank. Efficiency is directly related to the size of the air bubbles produced. Fine bubble systems have a higher efficiency. The diffused air system has a blower to produce large volumes of low pressure air (5 to 10 psi), air lines to carry the air to the aeration tank, and headers to distribute the air to the diffusers that release the air into the wastewater.

18.10.2.3 Settling Tank

Activated sludge systems are equipped with plain *settling tanks* designed to provide 2 to 4 h HDT.

18.10.2.4 Return Sludge

The return sludge system include pumps, a timer or variable speed drive to regulate pump delivery and a flow measurement device to determine actual flow rates.

18.10.2.5 Waste Sludge

In some cases, the WAS withdrawal is accomplished by adjusting valves on the return system. When a separate system is used it includes pumps, a timer or variable speed drive, and a flow measurement device.

18.10.3 Overview of Activated Sludge Process

The activated sludge process is a treatment technique in which wastewater and reused biological sludge full of living microorganisms are mixed and aerated. The biological solids are then separated from the treated wastewater in a clarifier and are returned to the aeration process or wasted.

The microorganisms are mixed thoroughly with the incoming organic material, and they grow and reproduce by using the organic material as food. As they grow and are mixed with air, the individual organisms cling together (flocculate). Once flocculated, they more readily settle in the secondary clarifiers.

The wastewater being treated flows continuously into an aeration tank where air is injected to mix the wastewater

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with the returned activated sludge and to supply the oxygen needed by the microbes to live and feed on the organics. Aeration can be supplied by injection through air diffusers in the bottom of tank or by mechanical aerators located at the surface.

The mixture of activated sludge and wastewater in the aeration tank is called the mixed liquor. The mixed liquor flows to a secondary clarifier where the activated sludge is allowed to settle.

The activated sludge is constantly growing, and more is produced than can be returned for use in the aeration basin. Some of this sludge must be wasted to a sludge handling system for treatment and disposal. The volume of sludge returned to the aeration basins is normally 40 to 60% of the wastewater flow. The rest is wasted.

18.10.4 Activated Sludge Process: Factors Affecting Operation

A number of factors affect the performance of an activated sludge system. These include the following:

1. Temperature
2. Return rates
3. Amount of oxygen available
4. Amount of organic matter available
5. pH
6. Waste rates
7. Aeration time
8. Wastewater toxicity

To obtain the desired level of performance in an activated sludge system, a proper balance must be maintained between the amount of food (organic matter), organisms (activated sludge), and oxygen (DO). The majority of problems with the activated sludge process result from an imbalance between these three items.

To fully appreciate and understand the biological process taking place in a normally functioning activated sludge process, the operator must have knowledge of the key players in the process: the organisms. This makes a certain amount of sense when you consider that the heart of the activated sludge process is the mass of settleable solids formed by aerating wastewater containing biological degradable compounds in the presence of microorganisms. Activated sludge consists of organic solids plus bacteria, fungi, protozoa, rotifers, and nematodes.

18.10.4.1 Growth Curve

To understand the microbiological population and its function in an activated sludge process, the operator must be familiar with the microorganism growth curve (see Section 11.12.5, Figure 11.15).

In the presence of excess organic matter, the microorganisms multiply at a fast rate. The demand for food and oxygen is at its peak. Most of this is used for the production new cells. This condition is known as the log growth phase (see Figure 11.15).

As time continues, the amount of food available for organisms declines. Floc begins to form, while the growth rate of bacteria and protozoa begins to decline. This is referred to as the declining growth phase (see Figure 11.15).

The endogenous respiration phase occurs as the food available becomes extremely limited and the organism mass begins to decline (see Figure 11.15). Some of the microorganisms may die and break apart, releasing organic matter that can be consumed by the remaining population.

The actual operation of an activated-sludge system is regulated by three factors: (1) the quantity of air supplied to the aeration tank, (2) the rate of activated-sludge recirculation, and (3) the amount of excess sludge withdrawn form the system. Sludge wasting is an important operational practice because it allows the operator to establish the desired concentration of MLSS, F:M ratio, and sludge age.

Note: Air requirements in an activated sludge basin are governed by (1) BOD loading and the desired removal effluent, (2) volatile suspended solids concentration in the aerator, and (3) suspended solids concentration of the primary effluent.

18.10.5 Activated Sludge Formation

The formation of activated sludge is dependent on three steps. The first step is the transfer of food from wastewater to organism. Second is the conversion of wastes to a usable form. Third is the flocculation step.

1. Transfer — Organic matter (food) is transferred from the water to the organisms. Soluble material is absorbed directly through the cell wall. Particulate and colloidal matter is adsorbed to the cell wall, where it is broken down into simpler soluble forms and absorbed through the cell wall.
2. Conversion — Food matter is converted to cell matter by synthesis and oxidation into end products such as CO_2, H_2O, NH_3, stable organic waste, and new cells.
3. Flocculation — Flocculation is the gathering of fine particles into larger particles. This process begins in the aeration tank and is the basic mechanism for removal of suspended matter in the final clarifier. The concentrated bio-floc that settles and forms the sludge blanket in the secondary clarifier is known as activated sludge.

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18.10.6 Activated Sludge: Performance-Controlling Factors

To maintain the working organisms in the activated sludge process, the operator must ensure that a suitable environment is maintained by being aware of the many factors influencing the process and by monitoring them repeatedly. Control is defined as maintaining the proper solids (floc mass) concentration in the aerator for the incoming water (food) flow by adjusting the return and waste sludge pumping rate and regulating the oxygen supply to maintain a satisfactory level of DO in the process.

18.10.6.1 Aeration

The activated sludge process must receive sufficient aeration to keep the activated sludge in suspension and to satisfy the organism oxygen requirements. Insufficient mixing results in dead spots, septic conditions, and loss of activated sludge.

18.10.6.2 Alkalinity

The activated sludge process requires sufficient alkalinity to ensure that pH remains in the acceptable range of 6.5 to 9.0. If organic nitrogen and ammonia are being converted to nitrate (nitrification), sufficient alkalinity must be available to support this process as well.

18.10.6.3 Nutrients

The microorganisms of the activated sludge process require nutrients (nitrogen, phosphorus, iron, and other trace metals) to function. If sufficient nutrients are not available, the process will not perform as expected. The accepted minimum ratio of carbon to nitrogen, phosphorus, and iron is 100 parts carbon to 5 parts nitrogen, 1 part phosphorus, and 0.5 parts iron.

18.10.6.4 pH

The pH of the mixed liquor should be maintained within the range of 6.5 to 9.0 (ideally 6.0 to 8.0). Gradual fluctuations within this range will normally not upset the process. Rapid fluctuations or fluctuations outside this range can reduce organism activity.

18.10.6.5 Temperature

As temperature decreases, activity of the organisms will also decrease. Cold temperatures also require longer recovery time for systems that have been upset. Warm temperatures tend to favor denitrification and filamentous growth.

Note: The activity level of bacteria within the activated sludge process increases with rise in temperature.

18.10.6.6 Toxicity

Sufficient concentrations of elements or compounds that enter a treatment plant that have the ability to kill the microorganisms (the activated sludge) are known as toxic waste (shock level). Common to this group are cyanides and heavy metals.

Note: A typical example of a toxic substance added by operators is the uninhabited use of chlorine for odor control or control of filamentous organisms (prechlorination). Chlorination is for disinfection. Chlorine is a toxicant and should not be allowed to enter the activated sludge process; it is not selective with respect to type of organisms damaged or killed. It may kill the organisms that should be retained in the process as workers. However, chlorine is very effective in disinfecting the plant effluent after treatment by the activated sludge process.

18.10.6.7 Hydraulic Loading

Hydraulic loading is the amount of flow entering the treatment process. When compared with the design capacity of the system, it can be used to determine if the process is hydraulically overloaded or underloaded. If more flow is entering the system than it was designed to handle, the system is hydraulically overloaded. If less flow is entering the system than it was designed to handle, the system is hydraulically underloaded. Generally, the system is more affected by overloading than by underloading.

Overloading can be caused by stormwater, infiltration of groundwater, excessive return rates, or many other causes. Underloading normally occurs during periods of drought or in the period following initial start-up when the plant has not reached its design capacity.

Excess hydraulic flow rates through the treatment plant will reduce the efficiency of the clarifier by allowing activated sludge solids to rise in the clarifier and pass over the effluent weir. This loss of solids in the effluent degrades effluent quality and reduces the amount of activated sludge in the system, reducing process performance.

18.10.6.8 Organic Loading

Organic loading is the amount of organic matter entering the treatment plant. It is usually measured as BOD. An organic overload occurs when the amount of BOD entering the system exceeds the design capacity of the system. An organic underload occurs when the amount of BOD

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entering the system is significantly less than the design capacity of the plant.

Organic overloading may occur when the system receives more waste than it was designed to handle. It can also occur when an industry or other contributor discharges more wastes to the system than originally planned. Wastewater treatment plant processes can also cause organic overloads returning high-strength wastes from the sludge treatment processes.

Regardless of the source, an organic overloading of the plant results in increased demand for oxygen. This demand may exceed the air supply available from the blowers. When this occurs, the activated sludge process may become septic.

Excessive wasting can also result in a type of organic overload. The food available exceeds the number of activated sludge organisms, resulting in increased oxygen demand and very rapid growth.

Organic underloading may occur when a new treatment plant is initially put into service. The facility may not receive enough waste to allow the plant to operate at its design level. Underloading can also occur when excessive amounts of activated sludge are allowed to remain in the system. When this occurs, the plant will have difficulty in developing and maintaining a good activated sludge.

18.10.7 Activated Sludge Modifications

First developed in 1913, the original activated sludge process has been modified over the years to provide better performance for specific operating conditions or with different influent waste characteristics.

18.10.7.1 Conventional Activated Sludge

1. Employing the conventional activated sludge modification requires primary treatment.
2. Conventional activated sludge provides excellent treatment, but large aeration tank capacity is required, and construction costs are high.
3. In operation, initial oxygen demand is high. The process is also very sensitive to operational problems (e.g., bulking).

18.10.7.2 Step Aeration

1. Step aeration requires primary treatment.
2. It provides excellent treatment.
3. Operation characteristics are similar to conventional.
4. It distributes organic loading by splitting influent flow.
5. It reduces oxygen demand at the head of the system.
6. It reduces solids loading on settling tank.

18.10.7.3 Complete Mix

1. May or may not include primary treatment.
2. Distributes waste, return, and oxygen evenly throughout tank.
3. Aeration may be more efficient.
4. Maximizes tank use.
5. Permits a higher organic loading.

Note: During the complete mix, activated sludge process organisms are in declining phase on growth curve.

18.10.7.4 Pure Oxygen

1. Requires primary treatment.
2. Permits higher organic loading.
3. Uses higher solids levels.
4. Operates at higher F/M ratios.
5. Uses covered tanks.
6. Potential safety hazards (pure oxygen).
7. Oxygen production is expensive.

18.10.7.5 Contact Stabilization

1. Contact stabilization does not require primary treatment.
2. During operation, organisms collect organic matter (during contact).
3. Solids and activated sludge are separated from flow via settling.
4. Activated sludge and solids are aerated for 3 to 6 h (stabilization).

Note: Return sludge is aerated before it is mixed with influent flow.

5. The activated sludge oxidizes available organic matter.
6. While the process is complicated to control, it requires less tank volume than other modifications and can be prefabricated as a package unit for flows of 0.05 to 1.0 MGD.
7. A disadvantage is that common process control calculations do not provide usable information.

18.10.7.6 Extended Aeration

1. Does not require primary treatment.
2. Used frequently for small flows such as schools and subdivisions.
3. Uses 24-h aeration.
4. Produces low BOD effluent.
5. Produces the least amount of WAS.

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TABLE 18.5
Activated Sludge Modifications

Parameter	Conventional	Contact Stabilization	Extended Aeration	Oxidation Ditch
Aeration time (h)	4–8	0.5–1.5 (contact) 3–6 (reaeration)	24	24
Settling time (h)	2–4	2–4	2–4	2–4
Return rate (% of influent flow)	25–100	25–100	25–100	25–100
MLSS (mg/L)	1500–4000	1000–3000 3000–8000	2000–6000	2000–6000
DO (mg/L)	1–3	1–3	1–3	1–3
SSV_{30} (mL/L)	400–700	400–700 (contact)	400–700	400–700
F:M ratio (lb BOD_5/lb MLVSS)	02–0.5	0.2–0.6 (contact)	0.05–0.15	0.05–0.15
MCRT (whole system [d]])	5–15	N/A	20–30	20–30
% Removal BOD_5	85–95%	85–95%	85–95%	85–95%
% Removal TSS	85–95%	85–95%	85–95%	85–95%
Primary treatment	Yes	No	No	No

N/A = not available.

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

6. Process is capable of achieving 95% or more removals of BOD.
7. Can produce effluent low in organic and ammonia nitrogen.

18.10.7.7 Oxidation Ditch

1. Does not require primary treatment.
2. The oxidation ditch process is similar to the extended aeration process.

Table 18.5 lists the process parameters for each of the four most commonly used activated sludge modifications.

18.10.8 Activated Sludge: Process Control Parameters

In operating an activated sludge process, the operator must be familiar with the many important process control parameters that must be monitored frequently and adjusted occasionally to maintain optimal performance.

18.10.8.1 Alkalinity

Monitoring alkalinity in the aeration tank is essential to control of the process. Insufficient alkalinity will reduce organism activity and may result in low effluent pH and, in some cases, extremely high chlorine demand in the disinfection process.

18.10.8.2 Dissolved Oxygen

The activated sludge process is an aerobic process that requires some DO be present at all times. The amount of oxygen required is dependent on the influent food (BOD), the activity of the activated sludge, and the degree of treatment desired.

18.10.8.3 pH

Activated sludge microorganisms can be injured or destroyed by wide variations in pH. The pH of the aeration basin will normally be in the range of 6.5 to 9.0. Gradual variations within this range will not cause any major problems; rapid changes of one or more pH units can have a significant impact on performance. Industrial waste discharges, septic wastes, or significant amounts of stormwater flows may produce wide variations in pH.

pH should be monitored as part of the routine process control-testing schedule. Sudden changes or abnormal pH values may indicate an industrial discharge of strongly acidic or alkaline wastes. Because these wastes can upset the environmental balance of the activated sludge, the presence of wide pH variations can result in poor performance.

Processes undergoing nitrification may show a significant decrease in effluent pH.

18.10.8.4 Mixed Liquor Suspended Solids, Mixed Liquor Volatile Suspended Solids, and Mixed Liquor Total Suspended Solids

The MLSS or MLVSS can be used to represent the activated sludge or microorganisms present in the process. Process control calculations, such as sludge age and SVI, cannot be calculated unless the MLSS is determined.

Adjust the MLSS and MLVSS by increasing or decreasing the waste sludge rates.

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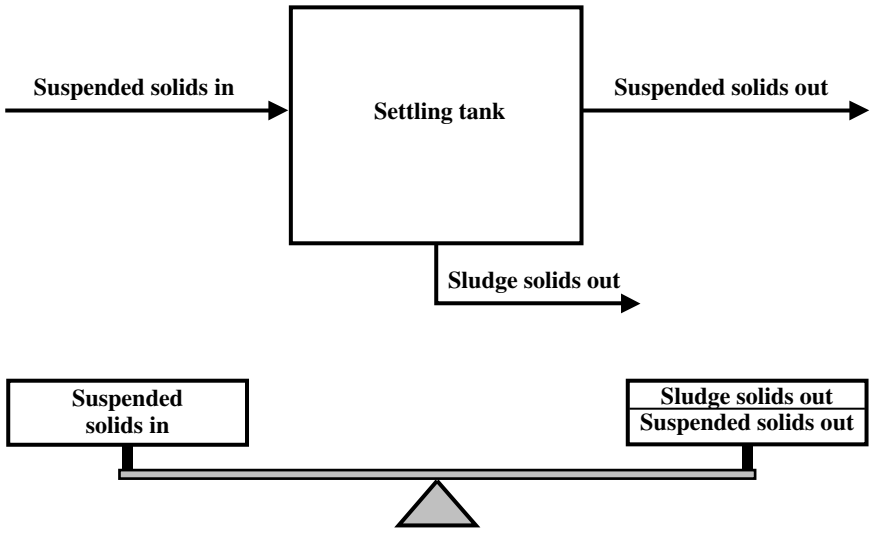

FIGURE 18.11 Settling tank mass balance. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

The mixed liquor total suspended solids (MLTSS) is an important activated sludge control parameter. To increase the MLTSS, for example, the operator must decrease the waste rate or increase the MCRT. The MCRT must be decreased to prevent the MLTSS from changing when the number of aeration tanks in service is reduced.

Note: In performing the Gould sludge age test, assume that the source of the MLTSS in the aeration tank is influent solids.

18.10.8.5 Return Activated Sludge Rate and Concentration

The sludge rate is a critical control variable. The operator must maintain a continuous return of activated sludge to the aeration tank or the process will show a drastic decrease in performance. If the rate is too low, solids remain in the settling tank, resulting in solids loss and a septic return. If the rate is too high, the aeration tank can become hydraulically overloaded, causing reduced aeration time and poor performance.

The return concentration is also important because it may be used to determine the return rate required to maintain the desired MLSS.

18.10.8.6 Waste Activated Sludge Flow Rate

Because the activated sludge contains living organisms that grow, reproduce, and produce waste matter, the amount of activated sludge is continuously increasing. If the activated sludge is allowed to remain in the system too long, the performance of the process will decrease. If too much activated sludge is removed from the system, the solids become very light and will not settle quickly enough to be removed in the secondary clarifier.

18.10.8.7 Temperature

Because temperature directly affects the activity of the microorganisms, accurate monitoring of temperature can be helpful in identifying the causes of significant changes in organization populations or process performance.

18.10.8.8 Sludge Blanket Depth

The separation of solids and liquid in the secondary clarifier results in a blanket of solids. If solids are not removed from the clarifier at the same rate they enter, the blanket will increase in depth. If this occurs, the solids may carry over into the process effluent. The sludge blanket depth may be affected by other conditions, such as temperature variation, toxic wastes, or sludge bulking.

The best sludge blanket depth is dependent upon such factors as hydraulic load, clarifier design, and sludge characteristics (see Figure 18.11). The best blanket depth must be determined on an individual basis by experimentation.

Note: In measuring sludge blanket depth, it is general practice to use a 15 to 20 ft long clear plastic pipe marked at 6-in. intervals, the pipe is equipped with a ball valve at the bottom.

18.10.9 Operational Control Levels

(Note: Much of the information in this section is based on *Activated Sludge Process Control*, Part II, 2nd ed., Virginia Water Control Board, 1990.)

The operator has two methods available to operate an activated sludge system. The operator can wait until the

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process performance deteriorates and make drastic changes, or the operator can establish *normal* operational levels and make minor adjustments to keep the process within the established operational levels.

Note: Control levels can be defined as the upper and lower values for a process control variable that can be expected to produce the desired effluent quality.

While the method will guarantee that plant performance will always be maintained within effluent limitations, the second method has a much higher probability of achieving this objective. This section discusses methods used to establish normal control levels for the activated sludge process.

Several major factors should be considered when establishing control levels for the activated sludge system. These include the following:

1. Influent characteristics
2. Industrial contributions
3. Process sidestreams
4. Seasonal variations
5. Required effluent quality

18.10.9.1 Influent Characteristics

Influent characteristics were discussed earlier. A major area to consider when evaluating influent characteristics is the nature and volume of industrial contributions to the system. Waste characteristics (BOD, solids, pH, metals, toxicity, and temperature), volume, and discharge pattern (continuous, slug, daily, weekly, etc.) should be evaluated when determining if a waste will require pretreatment by the industry or adjustments to operational control levels.

18.10.9.2 Industrial Contributions

One or more industrial contributors produce a significant portion of the plant loading (in many systems). Identifying and characterizing all industrial contributors is important. Remember that the volume of waste generated may not be as important as the characteristics of the waste. Extremely high-strength wastes can result in organic overloading and poor performance because of insufficient nutrient availability.

A second consideration is the presence of materials that even in small quantities are toxic to the process microorganisms or create a toxic condition in the plant effluent or plant sludge.

Industrial to a biological treatment system should be thoroughly characterized prior to acceptance, monitored frequently, and controlled by either local ordinance or by implementation of a pretreatment program.

18.10.9.3 Process Sidestreams

Process sidestreams are flows produced in other treatment processes that must be returned to the wastewater system for treatment prior to disposal. Examples of process sidestreams include the following:

1. Thickener supernatant
2. Aerobic and anaerobic digester supernatant
3. Liquids removed by sludge dewatering processes (filtrate, centrate, and subnate)
4. Supernatant from heat treatment and chlorine oxidation sludge treatment processes

Testing these flows periodically to determine both their quantity and strength is important. In many treatment systems, a significant part of the organic and/or hydraulic loading for the plant is generated by sidestream flows. The contribution of the plant sidestream flows can significantly change the operational control levels of the activated sludge system.

18.10.9.4 Seasonal Variations

Seasonal variations in temperature, oxygen solubility, organism activity, and waste characteristics may require several normal control levels for the activated sludge process. For example, during cold months of the year, aeration tank solids levels may have to be maintained at significantly higher level than are required during warm weather. Likewise, the aeration rate may be controlled by the mixing requirements of the system during the colder months and by the oxygen demand of the system during the warm months.

18.10.9.5 Control Levels at Start-Up

Control levels for an activated sludge system during start-up are usually based upon design engineer recommendations or information available from recognized reference sources. Although these levels provide a starting point, you should recognize that both the process control parameter sensitivity and control levels should be established on a plant-by-plant basis.

During the first 12 months of operation, you should evaluate all potential process control options, to determine the following:

1. Sensitivity to effluent quality changes
2. Seasonal variability
3. Potential problems

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18.10.10 Operator Observations: Influent and Aeration Tank

Wastewater operators are required to monitor or make certain observations of treatment unit processes to ensure optimum performance and make adjustments when required. In monitoring the operation of an aeration tank, the operator should look for three physical parameters (turbulence, surface foam and scum, and sludge color and odor), that aid in determining how the process is operating and indicate if any operational adjustments should be made.

This information should be recorded each time operational tests are performed. We summarize aeration tank and secondary settling tank observations in the following sections. Remember that many of these observations are very subjective and must be based upon experience. Plant personnel must be properly trained on the importance of ensuring that recorded information is consistent throughout the operating period.

18.10.10.1 Visual Indicators: Influent and Aeration Tank

18.10.10.1.1 Turbulence

Normal operation of an aeration basin includes a certain amount of turbulence. This turbulent action is required to ensure a consistent mixing pattern. Whenever excessive, deficient or nonuniform mixing occurs, adjustments may be necessary to airflow, or diffusers may need cleaning or replacement.

18.10.10.1.2 Surface Foam and Scum

The type, color and amount of foam or scum present may indicate the required wasting strategy to be employed. Types of foam include the following:

1. Fresh, crisp, white foam — Moderate amounts of crisp, white foam are usually associated with activated sludge processes producing an excellent final effluent. Adjustment: None, normal operation.
2. Thick, greasy, dark tan foam — A thick, greasy dark tan or brown foam or scum normally indicates an old sludge that is overoxidized, has a high mixed liquor concentration, and has a waste rate that is too high. Adjustment: Indicates old sludge, more wasting required.
3. White billowing foam — Large amounts of a white, soap suds-like foam indicate a very young, underoxidized sludge. Adjustment: Young sludge, less wasting required.

18.10.10.1.3 Sludge Color and Odor

Though not as reliable an indicator of process operations as foam, sludge colors and odor are also useful indicators. Colors and odors that are important include the following:

1. Chocolate brown or earthy odor — Indicates normal operation.
2. Light tan or brown or no odor — Indicates sand and clay from infiltration or inflow. Adjustment: Extremely young sludge, decrease wasting.
3. Dark brown or earthy odor — Indicates old sludge and high solids. Adjustment: Increase wasting.
4. Black color or rotten egg odor — Indicates septic conditions, low DO concentration, and an airflow rate that is too low. Adjustment: Increase aeration.

18.10.10.1.4 Mixed Liquor Color

A light chocolate brown mixed liquor color indicates a well-operated activated sludge process.

18.10.10.2 Final Settling Tank (Clarifier) Observations

Settling tank observations include flow pattern (normally uniform distribution), settling, amount and type of solids leaving with the process effluent (normally very low) and the clarity or turbidity of the process effluent (normally very clear).

Observations should include the following conditions:

1. Sludge bulking — Occurs when solids are evenly distributed throughout the tank and leaving over the weir in large quantities.
2. Sludge Solids Washout — Sludge blanket is down, but solids are flowing over the effluent weir in large quantities. Control tests indicate good quality sludge.
3. Clumping — Large clumps or masses of sludge (several inches or more) rise to the top of the settling tank.
4. Ashing — Fine particles of gray to white material flowing over the effluent weir in large quantities.
5. Straggler floc — Small, almost transparent, very fluffy, buoyant solids particles (1/8 to 1/4 in. diameter rising to the surface). Usually is accompanied by a very clean effluent. New growth is usually most noted in the early morning hours. Sludge age is slightly below optimum.
6. Pin floc — Very fine solids particles (usually less than 1/32 in. diameter) suspended throughout lightly turbid liquid. Usually the result of an overoxidized sludge.

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18.10.11 Process Control Testing and Sampling

The activated sludge process generally requires more sampling and testing to maintain adequate process control than any of the other unit processes in the wastewater treatment system. During periods of operational problems, both the parameters tested and the frequency of testing may increase substantially.

Process control testing may include the following:

1. Settleability testing to determine the settled sludge volume
2. Suspended solids testing to determine influent and MLSS
3. RAS solids and WAS concentrations
4. Determination of the volatile content of the mixed liquor suspended solids
5. DO and pH of the aeration tank
6. BOD and COD of the aeration tank influent and process effluent
7. Microscopic evaluation of the activated sludge to determine the predominant organism.

The following sections describe most of the common process control tests.

18.10.11.1 Aeration Influent Sampling

18.10.11.1.1 pH

pH is tested daily with a sample taken from the aeration tank influent and process effluent. pH is normally close to 7.0 (normal) with the best pH range from 6.5 to 8.5 (6.5 to 9.0 is satisfactory). A pH of less than 9.0 may indicate toxicity from an industrial waste contributor. A pH of greater than 6.5 may indicate loss of flocculating organisms, potential toxicity, industrial waste contributor, or acid storm flow. Keep in mind that the effluent pH may be lower because of nitrification.

18.10.11.1.2 Temperature

Temperature is important because it forecasts the following:

1. Temperature increases:
   A. Organism activity increases
   B. Aeration efficiency decreases
   C. Oxygen solubility decreases
2. Temperature decreases:
   A. Organism activity decreases
   B. Aeration efficiency increases
   C. Oxygen solubility increases

18.10.11.1.3 Dissolved Oxygen

The content of DO in the aeration process is critical to performance. DO should be tested at least daily (peak demand). Optimum is determined for individual plants, but normal is from 1 to 3 mg/L. If the system contains too little DO, the process will become septic. If it contains too much DO, energy and money is wasted.

18.10.11.1.4 Settled Sludge Volume (Settleability)

SSV is determined at specified times during sample testing. Both 30- and 60-min observations are used for control. Subscript numbers indicates settling time (e.g., SSV_{30} and SSV_{60}). The test is performed on aeration tank effluent sample.

$$SSV = \frac{\text{Milliliters of Settled Sludge}\,(1000\ \text{mL/L})}{\text{Milliliters of Sample}} \tag{18.27}$$

$$\%SSV = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliliters of Sample}} \tag{18.28}$$

Under normal conditions, sludge settles as a mass, producing clear supernatant with SSV_{60} in the range of 400 to 700 mL/L. When higher values are indicated, this may indicate excessive solids (old sludge) and bulking conditions. Rising solids (if sludge is well oxidized) may rise after 2 or more hours. However, rising solids in less than 1 h indicates a problem.

Note: Running the settleability test with a diluted sample can assist in determining if the activated sludge is old (too many solids) or bulking (not settling). Old sludge will settle to a more compact level when diluted.

18.10.11.1.4.1 Centrifuge Testing

The centrifuge test provides a quick, relatively easy control test for the solids level in the aerator, but does not usually correlate with MLSS results. Results are directly affected by variations in sludge quality.

18.10.11.1.5 Alkalinity

Alkalinity is essential to biological activity. Nitrification needs 7.3-mg/L alkalinity per milligrams per liter or TKN.

18.10.11.1.6 Biochemical Oxygen Demand

Testing showing an increase in BOD indicates increased organic loading; a decrease in BOD indicates decreased organic loading.

18.10.11.1.7 Total Suspended Solids

An increase in TSS indicates an increase in organic loading; a decrease TSS indicates a decrease in organic loading.

18.10.11.1.8 Total Kjeldahl Nitrogen

TKN determination is required to monitor process nitrification status and to determine alkalinity requirements.

18.10.11.1.9 Ammonia Nitrogen

Determination of ammonia nitrogen is required to monitor process nitrification status.

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TABLE 18.6
Process Condition vs. Organisms Present and Population

Process Condition	Organism Population
Poor BOD and TSS removal	Predominance of amoeba and flagellates
No floc formation	Mainly dispersed bacteria
Very cloudy effluent	A few ciliates present
Poor quality effluent	Predominance of amoeba and flagellates
Dispersed bacteria	Some free-swimming ciliates
Some floc formation	
Cloudy effluent	
Satisfactory effluent	Predominance of free-swimming ciliates
Good floc formation	Few amoeba and flagellates
Good settleability	
Good Clarity	
High-quality effluent	Predominance of stalked ciliates
Excellent floc formation	Some free-swimming ciliates
Excellent Settleability	A few rotifers
High effluent clarity	A few flagellates
Effluent High TSS and Low BOD	Predominance of rotifers
High settled sludge volume	Large numbers of stalked ciliates
Cloudy effluent	A few free-swimming ciliates
	No flagellates

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

18.10.11.1.10 Metals

Metal contents are measured to determine toxicity levels.

18.10.11.2 Aeration Tank

18.10.11.2.1 pH

Normal pH range in the aeration tank is 6.5 to 9.0 pH decreases indicate process sidestreams or insufficient alkalinity available.

18.10.11.2.2 Dissolved Oxygen

Normal DO range in an aeration tank is 1 to 3 mg/L. DO level decreases may indicate increased activity, increased temperature, increased organic loading, or decreased MLSS or MLVSS. An increase in DO could be indicative of decreased activity, decreased temperature, decreased organic loading, increased MLSS or MLVSS, or influent toxicity.

18.10.11.2.3 Dissolved Oxygen Profile

All DO profile readings should be less than 0.5 mg/L. Readings of greater than 0.5 mg/L indicate inadequate aeration or poor mixing.

18.10.11.2.4 Mixed Liquor Suspended Solids

The range of MLSS is determined by the process modification used. When MLSS levels increase, more solids, organisms, and an older, more oxidized sludge are typical.

18.10.11.2.5 Microscopic Examination

The activated sludge process can not operate as designed without the presence microorganisms. Microscopic examination of an aeration basin sample, which determines the presence and the type of microorganisms, is important. Different species prefer different conditions; therefore, the presence of different species can indicate process conditions.

Note: It is important to point out that during microscopic examination, identifying of all organisms present is not required, but identification of the predominant species is required.

Table 18.6 lists process conditions indicated by the presence and population of certain microorganisms.

18.10.11.2.5.1 Interpretation

Routine process control identification can be limited to the general category of organisms present. For troubleshooting more difficult problems, a more detailed study of organism distribution may be required (the knowledge required to perform this type of detailed study is beyond the scope of this text). The major categories of organisms found in the activated sludge are:

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1. Protozoa
2. Rotifers
3. Filamentous organisms

Note: Bacteria are the most important microorganisms in the activated sludge. They perform most of the stabilization or oxidation of the organic matter and are normally present in extremely large numbers. They are not, however, normally visible with a conventional microscope operating at the recommended magnification and are not included in the Table 18.6 list of indicator organisms.

Note: The presence of free-swimming and stalked ciliates, some flagellates, and rotifers in mixed liquor indicate a balanced, properly settling environment.

Protozoa

Protozoa are secondary feeders in the activated sludge process (secondary as feeders, but nonetheless definitely important to the activated sludge process). Their principal function is to remove (eat or crop) dispersed bacteria and help to produce a clear process effluent.

To help gain an appreciation for the role of protozoa in the activated sludge process consider the following explanation.

The activated sludge process is typified by the successive development of protozoa and mature floc particles. This succession can be indicated by the presence of the type of dominant protozoa present. At the start of the activated process (or recovery from an upset condition), the amoebas dominate.

Note: Amoebas have very flexible cell walls and move by shifting fluids within the cell wall. They predominate during process start-up or during recovery from severe plant upsets.

As the process continues uninterrupted or without upset, small populations of bacteria begin to grow in logarithmic fashion; as the population increases, they develop into mixed liquor. When this occurs, the flagellates dominate.

Note: Flagellated protozoa typically have a single hair-like flagella or tail that they use for movement. The flagellate predominates when the MLSS and bacterial populations are low and organic load is high. As the activated sludge gets older and denser, the flagellates decrease until they are seldom used.

When the sludge attains an age of about 3 d, lightly dispersed floc particles (flocculation grows fine solids into larger, more settleable solids) begin to form and bacteria increase. At this point, free-swimming ciliates dominate.

Note: The free-swimming ciliated protozoa have hair-like projections (cilia) that cover all or part of the cell. The cilia are used for motion and create currents that carry food to the organism. The free-swimming ciliates are sometimes divided into two subcategories: free swimmers and crawlers. The free swimmers are usually seen moving through the fluid portion of the activated sludge, while the crawlers appear to be walking or grazing on the activated sludge solids. The free-swimming ciliated protozoa usually predominate when a large number of dispersed bacteria are present that can be used as food. Their predominance indicates a process nearing optimum conditions and effluent quality.

The process continues with floc particles beginning to stabilize, taking on irregular shapes, and starting to show filamentous growth. At this stage, the crawling ciliates dominate. Eventually, mature floc particles develop and increase in size, and large numbers of crawling and stalked ciliates are present. When this occurs, the succession process has reached its terminal point.

The succession of protozoan and mature floc particle development just described details the occurrence of phases of development in a step-by-step progression. Protozoan succession is also based on other factors, including DO and food availability.

Probably the best way to understand protozoan succession based on DO and food availability is to view the wastewater treatment plant's aeration basin as a stream within a container. The saprobity system classifies the various phases of the activated sludge process in relation to the self-purification process that takes place in a stream. With this system, a clear relationship between the two processes based on available DO and food supply is evident.

Any change in the relative numbers of bacteria in the activated sludge process has a corresponding change to microorganism's population. Decreases in bacteria increase competition between protozoa and result in secession of dominant groups of protozoa.

The degree of success or failure of protozoa to capture bacteria depends on several factors. Those with more advanced locomotion capability are able to capture more bacteria. Individual protozoan feeding mechanisms are also important in the competition for bacteria. At the beginning of the activated sludge process, amoebas and flagellates are the first protozoan groups to appear in large numbers. They can survive on smaller quantities of bacteria because their energy requirements are lower than other protozoan types. Because few bacteria are present, competition for dissolved substrates is low. As the bacteria population increases, these protozoa are not able to compete for available food. This is when the next group of protozoa (the free-swimming protozoa) enters the scene.

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Free-swimming protozoa take advantage of the large populations of bacteria because they are better equipped with food-gathering mechanisms than the amoebas and flagellates. The free swimmers are important for their insatiable appetites for bacteria and are also important in floc formation. Secreting polysaccharides and mucoproteins that are absorbed by bacteria — which make the bacteria sticky through biological agglutination (biological gluing together) — allows them to stick together and, more importantly, to stick to floc. Large quantities of floc are prepared for removal form secondary effluent and are either returned to aeration basins or wasted.

The crawlers and stalked ciliates succeed the free swimmers.

Note: Stalked ciliated protozoa are attached directly to the activated sludge solids by a stalk. In some cases, the stalk is rigid and fixed in place, while in others, the organism can more (contract or expand the stalk) to change its position. The stalked ciliated protozoa normally have several cilia that are used to create currents that carry bacteria and organic matter to them. The stalked ciliated protozoa predominate when the dispersed bacteria population decreases and does not provide sufficient food for the free swimmers. Their predominance indicates a stable process, operating at optimum conditions.

The free swimmers are replaced in part because the increasing level of mature floc retards their movement. Additionally, the type of environment that is provided by the presence of mature floc is more suited to the needs of the crawlers and stalked ciliates. The crawlers and stalked ciliates also aid in floc formation by adding weight to floc particles, enabling removal.

Rotifers

Rotifers are a higher life form normally associated with clean, unpolluted waters. Significantly larger than most of the other organisms observed in activated sludge, rotifers can use other organisms, as well as organic matter, as their food source. Rotifers are usually the predominant organism; the effluent will usually be cloudy (pin of ash floc) and will have very low BOD.

Filamentous Organisms

Filamentous organisms (bacteria, fungi, etc.) occur whenever the environment of the activated sludge favors their predominance. They are normally present in small amounts and provide the basic framework for floc formation. When the environmental conditions (i.e., pH, nutrient levels, DO, etc.) favor their development, they become the predominant organisms. When this occurs, they restrict settling, and the condition known as bulking occurs.

Note: Microorganism examination of activated sludge is a useful control tool. In attempting to identify the microscopic contents of a sample, the operator should try to identify the predominant groups of organisms.

Note: During microscopic examination of the activated sludge, a predominance of amoebas indicates that the activated sludge is very young.

18.10.11.3 Settling Tank Influent

18.10.11.3.1 Dissolved Oxygen

The DO level of the activated sludge-settling tank should be 1 to 3 mg/L; lower levels may result in rising sludge.

18.10.11.3.2 pH

Normal pH range in an activated sludge-settling tank should be maintained between 6.5 to 9.0. Decreases in pH may indicate alkalinity deficiency.

18.10.11.3.3 Alkalinity

A lack of alkalinity in an activated sludge-settling tank will prevent nitrification.

18.10.11.3.4 Total Suspended Solids

MLSS sampling and testing is required for determining solids loading, mass balance, and return rates.

18.10.11.3.5 Settled Sludge Volume (Settleability)

SSV is determined at specified times during sample testing. Thirty- and 60-minute observations:

1. Normal operation — When the process is operating property, the solids will settle as a "blanket" (a mass), with a crisp or sharp edge between the solids and the liquor above. The liquid over the solids will be clear, with little or no visible solids remaining in suspension. Settled sludge volume at the end of 30 to 60 min will be in the range of 400 to 700 mL.
2. Old or overoxidized activated sludge — When the activated sludge is overoxidized, the solids will settle as discrete particles. The edge between the solids and liquid will be fuzzy, with a large number of visible solids (pin floc, ash floc, etc.) in the liquid. The settled sludge volume at the end of 30 or 60 min will be greater than 700 mL.
3. Young or under-oxidized activated sludge — When the activated sludge is under-oxidized, the solids settle as discrete particles, and the boundary between the solids and the liquid is poorly defined. Large amounts of small visible solids are suspended in the liquid. The settled

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sludge volume after 30 to 60 minutes will usually be less than 400 mL.

4. Bulking activated sludge — When the activated sludge is experiencing a bulking condition, very little or no settling is observed.

$$\text{SSV} = \frac{\text{Milliliters of Settled Sludge 1000 mL}}{\text{Milliliters of Sample}} \quad (18.29)$$

$$\%\text{SSV} = \frac{\text{Milliliters of Settled Sludge} \times 100}{\text{Milliliters of Sample}} \quad (18.30)$$

Note: Running the settleability test with a diluted sample can assist in determining if the activated sludge is old (too many solids) or bulking (not settling). Old sludge will settle to a more compact level when diluted.

18.10.11.3.6 Flow

Monitoring flow in settling tank influent is important for determination of mass balance.

18.10.11.3.7 Jar Tests

Jar tests are performed as required on settling tank influent and are beneficial in determining the best flocculant aid and appropriate doses to improve solids capture during periods of poor settling.

18.10.11.4 Settling Tank

18.10.11.4.1 Sludge Blanket Depth

As mentioned, sludge blanket depth refers to the distance from the surface of the liquid to the solids-liquid interface. It can also refer to the thickness of the sludge blanket as measured from the bottom of the tank to the solids-liquid interface. Part of the operator's sampling routine, this measurement is taken directly in the final clarifier. Sludge blanket depth is dependent upon hydraulic load, return rate, clarifier design, waste rate, sludge characteristics, and temperature. If all other factors remain constant, the blanket depth will vary with the amount of solids in the system and the return rate; it will vary throughout the day.

Note: Depth of sludge blanket provides an indication of sludge quality; it is used as a trend indicator. Many factors affect test result.

18.10.11.4.2 Suspended Solids and Volatile Suspended Solids

Suspended solids and volatile suspended solids concentrations of the mixed liquor (MLSS), RAS, and WAS are routinely sampled and tested because they are critical to process control.

18.10.11.5 Settling Tank Effluent

18.10.11.5.1 Biochemical Oxygen Demand and Total Suspended Solids

BOD and TSS testing is conducted variably (daily, weekly, and monthly). Increases indicate treatment performance is decreasing; decreases indicate treatment performance is increasing.

18.10.11.5.2 Total Kjeldahl Nitrogen

TKN sampling and testing is variable. An increase in TKN indicates nitrification is decreasing; a decrease in TKN indicates nitrification is increasing.

18.10.11.5.3 Nitrate Nitrogen

Nitrate nitrogen sampling and testing are variable. Increases in nitrate nitrogen indicate nitrification is increasing or industrial contribution of nitrates. A decrease indicates reduced nitrification.

18.10.11.5.4 Flow

Settling tank effluent flow is sampled and tested daily. Results are required for several process control calculations.

18.10.11.6 Return Activated Sludge and Waste Activated Sludge

18.10.11.6.1 Total Suspended Solids and Volatile Suspended Solids

TSS and total volatile suspended solids concentrations of the mixed liquor (MLSS), RAS, and WAS are routinely sampled (using either grab or composite samples) and tested, because they are critical to process control.

The results of the suspended and volatile suspended tests can be used directly or to calculate such process control figures as MCRT or ratio F/M ratio. In most situations, increasing the MLSS produces an older, denser sludge, while decreasing MLSS produces a younger, less dense sludge.

Note: Control of the sludge wasting rate by constant MLVSS concentration involves maintaining a certain concentration of volatile suspended solids in the aeration tank.

Note: The activated sludge aeration tank should be observed daily. Included in this daily observation should be a determination of the type and amount of foam, mixing uniformity, and color.

18.10.11.6.2 Flow

Test the flow of RAS daily. Test results are required to determine mass balance and for control of sludge blanket, MLSS, and MLVSS. For WAS, flow is sampled and tested whenever sludge is wasted. Results are required to determine mass balance and to control solids level in process.

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18.10.12 Process Control Adjustments

In the routine performance of their duties, wastewater operators make process control adjustments to various unit processes, including the activated sludge process. In the following a summary is provided of the process controls available for the activated sludge process and the result that will occur from adjustment of each.

1. Process control: Return rate
   A. Condition: Return rate is too high.
      Results:
      1. Hydraulic overloading of aeration and settling tanks.
      2. Reduced aeration time.
      3. Reduced settling time.
      4. Loss of solids over time.
   B. Condition: Return rate is too low.
      Results:
      1. Septic return.
      2. Solids buildup in settling tank.
      3. Reduced MLSS in aeration tank.
      4. Loss of solids over weir.
2. Process control: Waste rate
   A. Condition: Waste rate is too high.
      Results:
      1. Reduced MLSS.
      2. Decreased sludge density.
      3. Increased SVI.
      4. Decreased MCRT.
      5. Increased F/M Ratio.
   B. Condition: Waste rate is too low.
      Results:
      1. Increased MLSS.
      2. Increased sludge density.
      3. Decreased SVI.
      4. Increased MCRT.
      5. Decreased F/M ratio.
3. Process control: Aeration rate
   A. Condition: Aeration rate is too high.
      Results:
      1. Wasted energy.
      2. Increased operating cost.
      3. Rising solids.
      4. Breakup of activated sludge.
   B. Condition: Aeration rate is too low.
      Results:
      1. Septic aeration tank.
      2. Poor performance.
      3. Loss of nitrification.

18.10.13 Troubleshooting Operational Problems

The most important dual function performed by the wastewater operator is the identification of process control problems and implementing the appropriate actions to correct the problems. In this section, typical aeration system operational problems are listed with their symptoms, causes, and the appropriate corrective actions required to restore the unit process to a normal or optimal performance level.

1. Symptom 1: The solids blanket is flowing over the effluent weir (classic bulking). Settleability test shows no settling.
   A. Cause: Organic overloading.
      Corrective action: Reduce organic loading.
   B. Cause: Low pH.
      Corrective action: Add alkalinity.
   C. Cause: Filamentous growth.
      Corrective action: Add nutrients. Add chlorine or peroxide to return.
   D. Cause: Nutrient deficiency.
      Corrective action: Add nutrients.
   E. Cause: Toxicity.
      Corrective action: Identify source. Implement pretreatment.
   F. Cause: Overaeration.
      Corrective action: Reduce aeration during low flow periods.
2. Symptom 2: Solids settled properly in settleability test, but large amounts of solids are lost over effluent weir.
   A. Cause: Billowing solids due to short-circuiting.
      Corrective action: Identify short circuiting cause and eliminate if possible.
3. Symptom 3: Large amounts of small pinhead sized solids are leaving the settling tank.
   A. Cause: Old sludge.
      Corrective action: Reduce sludge age (gradual change is best). Increase waste rate.
   B. Cause: Excessive turbulence.
      Corrective Action: Decrease turbulence (adjust aeration during low flows).
4. Symptom 4: Large amount of light floc (low BOD and high solids) leaving settling tank.
   A. Cause: Extremely old sludge.
      Corrective action: Reduce age. Increase waste.
5. Symptom 5: Large amounts of small translucent particles (1/16 to 1/8 in.) are leaving the settling tank.
   A. Cause: Rapid solids growth.
      Corrective action: Increase sludge age.
   B. Cause: Slightly young activated sludge.
      Corrective action: Decrease waste.

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6. Symptom 6: Solids are settling properly, but rise to surface within a short time. Many small (1/4 in.) to large (several feet) clumps of solids on surface of settling tank.
   A. Cause: Denitrification.
      Corrective action: Increase rate of return. Adjust sludge age to eliminate nitrification.
   B. Cause: Overaeration.
      Corrective action: Reduce aeration.
7. Symptom 7: RAS has a rotten egg odor.
   A. Cause: Return is septic.
      Corrective action: Increase aeration rate
   B. Cause: Return rate is too low.
      Corrective action: Increase rate of return.
8. Symptom 8: Activated sludge organisms die during a short time.
   A. Cause: Influent contained toxic material.
      Corrective action: Isolate activated sludge (if possible). Return all available solids. Stop wasting. Increase return rate. Implement pretreatment program.
9. Symptom 9: Surface of aeration tank covered with thick, greasy foam.
   A. Cause: Extremely old activated sludge.
      Corrective action: Reduce activated sludge age. Increase wasting. Use foam control sprays.
   B. Cause: Excessive grease and oil in system.
      Corrective action: Improve grease removal. Use foam control sprays. Implement pretreatment program.
   C. Cause: Froth forming bacteria.
      Corrective action: Remove froth forming bacteria.
10. Symptom 10: Large clouds of billowing white foam on the surface of the aeration tank.
   A. Cause: Young activated sludge.
      Corrective action: Increase sludge age. Decrease wasting. Use foam control sprays.
   B. Cause: Low solids in aeration tank.
      Corrective action: Increase sludge age. Decrease wasting. Use foam control sprays.
   C. Cause: Surfactants (detergents).
      Corrective action: Eliminate surfactants. Use foam control sprays. Add antifoam.

18.10.14 Process Control Calculations

As with other wastewater treatment unit processes, process control calculations are important tools used by the operator to optimize and control process operations. In this section we review the most frequently used activated sludge calculations.

18.10.14.1 Settled Sludge Volume

SSV is the volume that a settled activated sludge occupies after a specified time. The settling time may be shown as a subscript (i.e., SSV_{60} indicates the reported value was determined at 60 min). SSV can be determined for any time interval; the most common values are the 30-min reading (SSV_{30}) and 60-min reading (SSV_{60}). The settled sludge volume can be reported as milliliters of sludge per liter of sample or as a percent of SSV.

$$\text{SVI}\ (\text{mL/L}) = \frac{\text{SSV}\ (\text{mL/L})}{\text{Sample Volume}\ (\text{L})} \tag{18.31}$$

Note: 1,000 mL = 1 L

$$\text{Sample Volume}\ (\text{l}) = \frac{\text{Sample Volume}\ (\text{mL})}{1000\ \text{ml/L}} \tag{18.32}$$

$$\%\ \text{Settled Sludge Volume} = \frac{\text{Settled Sludge Volum, MI} \times 100}{\text{Sample Volume, MI}} \tag{18.33}$$

Example 18.38

Problem:

Using the information provided in the table, calculate the SSV_{30} and the % SSV_{60}.

Time	Milliliters
Start	2500
15 min	2250
30 min	1800
45 min	1700
60 min	1600

Solution:

$$SSV_{30} = \frac{1800\ \text{mL}}{2.5\ \text{L}} = 720\ \text{mL/L}$$

$$\%\ SSV_{60} = \frac{1600\ \text{mL} \times 100}{2500\ \text{mL}} = 64\%$$

18.10.14.2 Estimated Return Rate

There are many different methods available for estimation of the proper return sludge rate. A simple method described in the *Operation of Wastewater Treatment Plants, Field Study Program* (1986) — developed by the California State University, Sacramento — uses the $\%SSV_{60}$. This value can provide an approximation of the appropriate RAS rate. The results of this calculation can then be adjusted based upon sampling and visual observations to develop the optimum return sludge rate:

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Note: The $\%SSV_{60}$ must be converted to a decimal percent and total flow rate (wastewater flow and current return rate in million gallons per day must be used).

$$\text{Estimated Return Rate (MGD)} = [\text{Influent Flow (MGD)} + \text{Curent Return Flow (MGD)}] \times \%SSV_{60}$$

This equation:

1. Assumes $\%SSV_{60}$ is representative.
2. Assumes return rate, in per cent equals $\%SSV_{60}$.
3. Actual return rate is normally set slightly higher to ensure organisms are returned to the aeration tank as quickly as possible. The rate of return must be adequately controlled to prevent the following:
   A. Aeration and settling hydraulic overloads.
   B. Low MLSS levels in the aerator.
   C. Organic overloading of aeration.
   D. Solids loss due to excessive sludge blanket depth.

EXAMPLE 18.39

Problem:

The influent flow rate is 4.2 MGD and the current return activated sludge flow rate is 1.5 MGD. The SSV_{60} is 38%. Based upon this information what should be the return sludge rate in million gallons per day?

Solution:

$$\text{Estimated Return Rate (MGD)} = [4.2 \text{ MGD} + 1.5 \text{ MGD}] \times 0.38 = 2.2 \text{ MGD}$$

18.10.14.3 Sludge Volume Index

SVI is a measure of the settling quality (a quality indicator) of the activated sludge. As the SVI increases the sludge settles slower, does not compact as well, and is likely to result in an increase in effluent suspended solids. As the SVI decreases the sludge becomes denser, settling is more rapid, and the sludge becomes older. SVI is the volume in milliliters occupied by 1 g of activated sludge. SSV, (milliliters per liter) and the MLSS (milligrams per liter) are required for this calculation:

$$\text{Sludge Volume Index (SVI)} = \frac{\text{SSV, MI/L} \times 1000}{\text{MLSS mg/L}} \tag{18.34}$$

EXAMPLE 18.40

Problem:

The SSV_{30} is 365 mL/L and the MLSS is 2365 mg/L. What is the SVI?

Solution:

$$\text{Sludge Volume Index} = \frac{365 \text{ MI/L} \times 1000}{2365 \text{ mg/L}} = 154.3$$

In this example, SVI equals 154.3. What does this mean? It means is that the system is operating normally with good settling and low effluent turbidity. We know this because we compare the result with the parameters listed below to obtain the expected condition (the result).

SVI Value	Expected Condition (Indications in Parentheses)
Less than 100	Old sludge — possible pin floc (effluent turbidity increasing)
100–200	Normal operation — good Settling (low effluent turbidity)
Greater than 250	Bulking sludge — poor settling (high effluent turbidity)

The SVI is best used as a trend indicator to evaluate what is occurring compared to previous SVI values. Based upon this evaluation, the operator may determine if the SVI trend is increasing or decreasing (refer to the chart below).

SVI Value	Result	Adjustment
Increasing	Sludge is becoming less dense Sludge is either younger or bulking Sludge will settle more slowly Sludge will compact less	Decrease waste Increase return rate
Decreasing	Sludge is becoming denser Sludge is becoming older Sludge will settle more rapidly Sludge will compact more with no other process changes	Increase waste rate Decrease return rate
Holding constant	No changes indicated Sludge should continue to have Its current characteristics	

18.10.14.4 Waste Activated Sludge

The quantity of solids removed from the process as WAS, is an important process control parameter that operators need to be familiar with. More importantly, operators must also know how to calculate it and can do so with the following equation:

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$$\text{Waste (lb/d)} = \text{WAS Concentration (mg/L)} \times \text{WAS Flow (MGD)} \times 8.34 \text{ lb/MG/mg/L} \quad (18.35)$$

EXAMPLE 18.41

Problem:

The operator wastes 0.44 MGD of activated sludge. The WAS has a solids concentration of 5540 mg/L. How many pounds of WAS are removed from the process?

Solution:

$$\text{Waste (lb/d)} = 5540 \text{ mg/L} \times 0.44 \text{ MGD} \times 8.34 \text{ lb/MG/mg/L} = 20{,}329.6 \text{ lb/d}$$

18.10.14.5 Food to Microorganism Ratio (F:M Ratio)

The F:M ratio is a process control calculation used in many activated sludge facilities to control the balance between available food materials (BOD or COD) and available organisms (MLVSS). The COD test is sometimes used, because the results are available in a relatively short period of time.

To calculate the F:M ratio, the following information is required and Equation 18.46 is used:

1. Aeration tank influent flow rate (MGD)
2. Aeration tank influent BOD or COD (mg/L)
3. Aeration tank MLVSS (mg/L)
4. Aeration tank volume (MG)

$$\text{F/M Ratio} = \frac{\text{Prim. Eff. COD/BOD mg/L} \times \text{Flow MGD} \times 8.34 \text{ lb/mg/L/MG}}{\text{MLVSS mg/L} \times \text{Aerator Volume, MG} \times 8.34 \text{ lb/mg/L/MG}} \quad (18.36)$$

Typical F/M ratio for activated sludge processes is shown in the chart below:

Process	lb BOD/lb MLVSS	lb COD/lb MLVSS
Conventional	0.2–0.4	0.5–1.0
Contact stabilization	0.2–0.6	0.5–1.0
Extended aeration	0.05–0.15	0.2–0.5
Oxidation ditch	0.05–0.15	0.2–0.5
Pure oxygen	0.25–1.0	0.5–2.0

EXAMPLE 18.42

Problem:

Given the following data, what is the F:M ratio?

Primary effluent flow	2.5 MGD	Aeration volume	0.65 MG
Primary effluent BOD	145 mg/L	Settling volume	0.30 MG
Primary effluent TSS	165 mg/L	MLSS	3,650 mg/L
Effluent flow	2.2 MGD	MLVSS	2,550 mg/L
Effluent BOD	22 mg/L	% Waste Volatile	71%
Effluent TSS	16 mg/L	Desired F:M	0.3

Solution:

$$\text{F/M Ratio} = \frac{145 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34 \text{ lb/mg/L/MG}}{2550 \text{ mg/L} \times 0.65 \text{ MG} \times 8.34 \text{ lb/mg/L/MG}} = 0.19 \text{ lb BOD/lb MLVSS}$$

Note: If the MLVSS concentration is not available, it can be calculated if %VM of the MLSS is known (see Equation 18.37):

$$\text{MLVSS (mg/L)} = \text{MLSS} \times \text{\%VM (decimal)} \quad (18.37)$$

Note: The F value in the F:M ratio for computing loading to an activated sludge process can be either BOD or COD. Remember that the reason for sludge production in the activated sludge process is to convert BOD to bacteria. One advantage of using COD over BOD for analysis of organic load is that COD is more accurate.

EXAMPLE 18.43

Problem:

The aeration tank contains 2985 mg/L of MLSS. Laboratory tests indicate the MLSS is 66% volatile matter. What is the MLVSS concentration in the aeration tank?

Solution:

$$\text{MLVSS (mg/L)} = 2985 \text{ mg/L} \times 0.66 = 1970 \text{ mg/L}$$

18.10.14.5.1 F:M Ratio Control

Maintaining the F:M ratio within a specified range can be an excellent control method. Although the F:M ratio is affected by adjustment of the return rates, the most practical method for adjusting the ratio is through waste rate adjustments. Increasing the rate will decrease the MLVSS and increase the F:M ratio. Decreasing the waste rate will increase the MLVSS and decrease the F:M ratio

18.10.14.5.2 Establishing Desired F:M Levels

The desired F:M ratio must be established on a plant-by-plant basis. Comparison of F:M ratios with plant effluent quality is the primary means to identify the most effective range for individual plants, when the range of F:M values that produce the desired effluent quality is established.

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18.10.14.5.3 Required MLVSS Quantity

The pounds of MLVSS required in the aeration tank to achieve optimum F:M ratio can be determined from the average influent food (BOD or COD) and the desired F:M ratio:

$$\text{MLVSS (lb)} = \frac{\text{Primary Effluent of BOD or COD (mg/L)} \times \text{Q (MGD)} \times 8.34 \text{ lb/gal}}{\text{Desired F/M Ratio (lb BOD or COD/lb MLVSS)}} \tag{18.38}$$

The required pounds of MLVSS determined by this calculation can then be converted to a concentration value with the following equation:

$$\text{MLVSS (mg/L)} = \frac{\text{Desired MLVSS (lb)}}{\text{Aeration Volume (MG)} \times 8.34 \text{ lb/mg/L/MG}} \tag{18.39}$$

Example 18.44

Problem:

The aeration tank influent flow is 4.0 MGD, and the influent COD is 145 mg/L. The aeration tank volume is 0.65 MG. The desired F:M ratio is 0.3 lb COD/lb MLVSS.

1. How many pounds of MLVSS must be maintained in the aeration tank to achieve the desired F:M ratio?
2. What is the required concentration of MLVSS in the aeration tank?

Solution:

1. $$\text{MLVSS (lb)} = \frac{145 \text{ mg/L} \times 4.0 \text{ MGD} \times 8.34 \text{ lb/gal}}{0.3 \text{ lb COD/lb MLVSS}} = 16{,}124 \text{ lb MLVSS}$$

2. $$\text{MLVSS, mg/L} = \frac{16{,}124 \text{ MLVSS}}{[0.65 \text{ MG} \times 8.34 \text{ lb/gal}]} = 2.974 \text{ mg/L MLVSS}$$

18.10.14.5.4 Calculating Waste Rates Using F:M Ratio

Maintaining the desired F:M ratio is accomplished by controlling the MLVSS level in the aeration tank. This may be accomplished by adjustment of return rates, but the most practical method is by proper control of the waste rate:

$$\text{Waste Volume of Solids (lb/d)} = \text{Actual MLVSS (lb)} - \text{Desired MLVSS (lb)} \tag{18.40}$$

If the desired MLVSS is greater than the actual MLVSS, wasting is stopped until the desired level is achieved.

Practical considerations require that the required waste quantity be converted to a required volume to waste per day. This is accomplished by converting the waste pounds to flow rate in million gallons per day or gallons per minute.

$$\text{Waste, MGD} = \frac{\text{Waste Volatile, lb/d}}{[\text{Waste Volatile Concentration, mg/L} \times 8.34 \text{ lb/gal}]} \tag{18.41}$$

Note: When F:M ratio is used for process control, the volatile content of the waste activated sludge should be determined.

Example 18.45

Problem:

Given the following information, determine the required waste rate in gallons per minute to maintain an F:M ratio of 0.17 lb COD/lb MLVSS:

Primary effluent COD	140 mg/L
Primary effluent flow	2.2 MGD
MLVSS	3549 mg/L
Aeration tank volume	0.75 MG
Waste volatile concentration	4440 mg/L (volatile solids)

Solution:

$$\text{Actual MLVSS (lb)} = 3.549 \text{ mg/L} \times 0.75 \text{ MG} \times 8.34 \text{ lb/gal} = 22{,}199 \text{ lb}$$

$$\text{Required MLVSS, lb} = \frac{140 \text{ mg/L} \times 2.2 \text{ MGD} \times 8.34 \text{ lb/gal}}{0.17 \text{ lb COD/lb MLVSS}} = 15.110 \text{ lb MLVSS}$$

$$\text{Waste, lb/d} = 22{,}199 \text{ lb} - 15{,}110 \text{ lb} = 7{,}089 \text{ lb}$$

$$\text{Waste, MGD} = \frac{7{,}089 \text{ lb/d}}{[4440 \text{ mg/L} \times 8.34 \text{ lb/gal}]} = 0.19 \text{ MGD}$$

$$\text{Waste, gpm} = \frac{0.19 \text{ MGD} \times 1{,}000{,}000 \text{ gpd/MGD}}{1440 \text{ min/d}} = 132 \text{ gpm}$$

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18.10.14.6 Mean Cell Residence Time (MCRT)

MCRT (sometimes called SRT) is a process control calculation used for activated sludge systems. The MCRT calculation illustrated in Example 18.46 uses the entire volume of the activated sludge system (aeration and settling). Equation 18.52 is used to calculate the MCRT:

$$\text{MCRT (d)} = \frac{\text{MLSS (mg/L)} \times [\text{Aeration Volume (MG)} + \text{Clarifier Volume (MG)}] \times 8.34\ \text{lb/mg/L/MG}}{[\text{WAS (mg/L)} \times \text{WAS Flow (MGD)} \times 8.34\ \text{lb/mg/L/MG}] + [\text{TSS}_{\text{out}}\ \text{(mg/L)} \times \text{Q (MGD)} \times 8.34\ \text{lb/mg/L/MG}]} \quad (18.42)$$

Note: MCRT can be calculated using only the aeration tank solids inventory. When comparing plant operational levels to reference materials, it is important to determine which calculation the reference manual uses to obtain its example values. Other methods are available to determine the clarifier solids concentration. The simplest method assumes that the average suspended solids concentration is equal to the aeration tank's solids concentration.

EXAMPLE 18.46

Problem:

Given the following data, what is the MCRT?

Influent flow	4.2 MGD	Aeration volume	1.20 MG
Influent BOD	135 mg/L	Settling volume	0.60 MG
Influent TSS	150 mg/L	MLSS	3,350 mg/L
Effluent flow	4.2 MGD	Waste rate	0.080 MGD
Effluent BOD	22 mg/L	Waste concentration	6100 mg/L
Effluent TSS	10 mg/L	Desired MCRT	8.5 d

$$\text{MCRT} = \frac{3350\ \text{mg/L} \times [1.2\ \text{MGD} + 0.6\ \text{MG}] \times 8.34\ \text{lb/mg/L/MG}}{[6100\ \text{mg/L} \times 0.08\ \times 8.34\ \text{lb/mg/L/MG}] + [10\ \text{mg/L}\ \times 4.2\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}]}$$

$$= 11.4\ \text{d}$$

18.10.14.6.1 Mean Cell Residence Time Control

Because it provides an accurate evaluation of the process condition and takes all aspects of the solids inventory into account, the MCRT is an excellent process control tool. Increases in the waste rate will decrease the MCRT, as will large losses of solids over the effluent weir. Reductions in waste rate will result in increased MCRT values.

Note: You should remember the following important process control parameters:

1. To increase F:M, decrease MCRT.
2. To increase MCRT, decrease waste rate.
3. MCRT is increased, MLTSS and 30-min setting increases.
4. Return sludge rate has no impact on MCRT.
5. MCRT has no impact on F:M change when the number of aeration tanks in service is reduced.

18.10.14.6.2 Typical MCRT Values

The following chart lists the various aeration process modifications and associated MCRT values.

Process	MCRT (d)
Conventional	5–15
Step aeration	5–15
Contact stabilization (contact)	5–15
Extended aeration	20–30
Oxidation ditch	20–30
Pure oxygen	8–20

18.10.14.6.3 Control Values for MCRT

Control values for the MCRT are normally established based on effluent quality. Once the MCRT range required to produce the desired effluent quality is established, it can be used to determine the waste rate required to maintain it.

18.10.14.6.4 Waste Quantities and Requirements

MCRT for process control requires the determination of the optimum range for MCRT values. This is accomplished by comparison of the effluent quality with MCRT values. When the optimum MCRT is established, the quantity of solids to be removed (wasted) is determined by

$$\text{Waste Quantity}\left(\text{lb/d}\right) = \frac{\text{MLSS}\left(\text{mg/L}\right) \times \left[\text{Aeration Volume}\left(\text{MG}\right) + \text{Clarifier Volume}\left(\text{MG}\right)\right] \times 8.34\ \text{lb/mg/L/MG}}{\text{Desired MCRT}\left(\text{d}\right)} - \left[\text{TSS}_{\text{out}}\left(\text{mg/L}\right) \times \text{Q}\left(\text{MGD}\right) \times 8.34\ \text{lb/mg/L/MG}\right] \quad (18.43)$$

EXAMPLE 18.47

Problem:

Given the following data, determine the waste rate to maintain an MCRT of 8.6 d:

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MLSS	3400 mg/L
Aeration volume	1.4 MG
Clarifier volume	0.5 MG
Effluent TSS	10 mg/L
Effluent flow	5.0 MGD

Solution:

$$\text{Waste Quantity (lb/d)} = 5848 \text{ lb}$$

$$\frac{3400\ (\text{mg/L}) \times [1.4\ \text{MG} + 0.5\ \text{MG}] \times 8.34\ \text{lb/mg/L/MG}}{8.6\ \text{d}} -$$

$$[10\ \text{mg/L} \times 5.0\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}]$$

18.10.14.6.4.1 Waste Rate in Million Gallons/Day

When the quantity of solids to be removed from the system is known, the desired waste rate in million gallons per day can be determined. The unit used to express the rate (MGD, gal/d, and gal/min) is a function of the volume of waste to be removed and the design of the equipment.

$$\text{Waste (MGD)} = \frac{\text{Waste Pounds/d}}{\text{WAS Concentrations, mg/L} \times 8.34} \tag{18.44}$$

$$\text{Waste (gal/min)} = \frac{\text{Waste (MGD)} \times 1{,}000{,}000\ \text{gal/d/MGD}}{1440\ \text{min/d}} \tag{18.45}$$

EXAMPLE 18.48

Problem:

Given the following data, determine the required waste rate to maintain an MCRT of 8.8 d:

MLSS	2500 mg/L
Aeration volume	1.2 MG
Clarifier volume	0.2 MG
Effluent TSS	11 mg/L
Effluent flow	5.0 MGD
Waste concentrations	6000 mg/L

(18.46)

Solution:

$$\text{Waste Quantity (lb/d)}$$

$$= \frac{2500\ \text{mg/L} \times [1.2\ \text{MG} + 0.2\ \text{MG}] \times 8.34\ \text{lb/mg/L/MG}}{8.8\ \text{d}} -$$

$$[10\ \text{mg/L} \times 5.0\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}]$$

$$= 3317\ \text{lb/d} - 459\ \text{lb/d}$$

$$= 2858\ \text{lb/d}$$

$$\text{Waste (MGD)} = \frac{2858\ \text{lb/d}}{6000\ \text{mg/l} \times 8.34\ \text{lb/gal}} = 0.057\ \text{MGD}$$

$$\text{Waste (gal/min)} = \frac{0.57\ \text{MGD} \times 1{,}000{,}000\ \text{gal/d/MGD}}{1440\ \text{min/d}}$$

$$= 40\ \text{gal/min}$$

18.10.14.7 Mass Balance

Mass balance is based upon the fact that solids and BOD are not lost in the treatment system. In simple terms, the mass balance concept states that what comes in must equal waste that goes out. The concept can be used to verify operational control levels and determine if potential problems exist within the plant's process control monitoring program.

Note: If influent values and effluent values do not correlate within 10 to 15%, it usually indicates either a sampling or testing error or a process control discrepancy.

Mass balance procedures for evaluating the operation of a settling tank and a biological process are described in this section. Operators should recognize that although the procedures are discussed in reference to the activated sludge process, the concepts can be applied to any settling or biological process.

18.10.14.7.1 Mass Balance: Settling Tank Suspended Solids

The settling tank mass balance calculation assumes that no suspended solids are produced in the settling tank. Any settling tank operation can be evaluated by comparing the solids entering the unit with the solids leaving the tank as effluent suspended solids or as sludge solids (see Figure 18.11). If sampling and testing are accurate and representative, and process control and operation are appropriate, the quantity of suspended solids entering the settling tank should equal (±10%) the quantity of suspended solids leaving the settling tanks as sludge, scum, and effluent total suspended solids.

Note: In most instances, the amount of suspended solids leaving the process as scum is so small that it is ignored in the calculation.

18.10.14.7.1.1 Mass Balance Calculation

$$\text{TSS}_{\text{in}}\ (\text{lb/d}) = \text{TSS}_{\text{in}}\ (\text{mg/L}) \times \text{Q (MGD)} \times 8.34\ \text{lb/mg/L/MG}$$

$$\text{TSS}_{\text{out}}\ (\text{lb/d}) = \text{TSS}_{\text{out}}\ (\text{mg/L}) \times \text{Q (MGD)} \times 8.34\ \text{lb/mg/L/MG}$$

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$$\text{Sludge Solids}\,(\text{lb/d}) =$$

$$\text{Sludge Pumped}\,(\text{gal}) \times \%\text{Solids} \times 8.34\ \text{lb/mg/L/MG}$$

$$\%\text{Mass Balance} =$$

$$\frac{\left[\text{TSS}_{\text{in}}\,(\text{lb}) - \left(\text{TSS}_{\text{out}}\,(\text{lb}) + \text{Sludge Solids}\,(\text{lb})\right)\right] \times 100}{\text{TSS}_{\text{in}}\,(\text{lb})}$$

18.10.14.7.1.2 Explanation of Results

1. The mass balance is ±15% or less — The process is considered to be in balance. Sludge removal should be adequate with the sludge blanket depth remaining stable. Sampling is considered to be producing representative samples that are being tested accurately.
2. The mass balance is greater than ±15% — Indicates that more solids are entering the settling tank than are being removed. Sludge blanket depth should be increasing, effluent solids may also be increasing, and effluent quality in decreasing. If changes described are not occurring, the mass balance may indicate that sample type, location, times, or procedures and/or testing procedures are not producing representative results.
3. If the mass balance is greater than 15%, it indicates that fewer solids are entering the settling tank than are being removed. Sludge blanket depth should be decreasing; sludge solids concentration may also be decreasing. This could adversely impact sludge treatment processes. If changes described are not occurring, the mass may indicate that sample type, location, times, or procedures and/or testing procedures are not producing representative results.

EXAMPLE 18.49

Problem:

Given the following data, determine the solids mass balance for the settling tank:

Process	Extended Aeration (No Primary)	
Influent	Flow	2.6 MGD
	TSS	2445 mg/L
Effluent	Flow	2.6 MGD
	TSS	17 mg/L
Return	Flow	0.5 MGD
	TSS	8470 mg/L

Solution:

$$\text{Solids in}\,(\text{lb/d})$$

$$= 2445\ \text{mg/L} \times 2.6\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}$$

$$= 53{,}017\ \text{lb/d}$$

$$\text{Solids out}\,(\text{lb/d})$$

$$= 17\ \text{mg/L} \times 2.6\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}$$

$$= 369\ \text{lb/d}$$

$$\text{Sludge Solids out}\,(\text{lb/d})$$

$$= 8470\ \text{mg/L} \times 0.5\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}$$

$$= 35{,}320\ \text{lb/d}$$

$$\%\text{Mass Balance}$$

$$= \frac{[53{,}017\ \text{lb/d} - (396\ \text{lb/d} + 35{,}320\ \text{lb/d})] \times 100}{53{,}017\ \text{lb/d}}$$

$$= 32.7\%$$

The mass balance indicates:

1. The sampling point or collection procedure or laboratory procedure is producing inaccurate data upon which to make process control decisions.
2. More solids are entering the settling tank each day than are being removed. This should result in either:
   A. A solids buildup in the settling tank.
   B. A loss of solids over the effluent weir.

Investigate further to determine the specific cause of the imbalance.

18.10.14.7.2 Mass Balance: Biological Process

Solids are produced whenever biological processes are used to remove organic matter from wastewater (see Figure 18.11). Mass balance for an aerobic biological process must take into account both the solids removed by physical settling processes and the solids produced by biological conversion of soluble organic matter to insoluble suspended matter or organisms. Research has shown that the amount of solids produced per pound of BOD removed can be predicted based upon the type of process being used. Although the exact amount of solids produced can vary from plant to plant, research has developed a series of *K* factors that can be used to estimate the solids production for plants using a particular treatment process. These average factors provide a simple method to evaluate the effectiveness of a facility's process control program.

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TABLE 18.7
Conversion Factors *K*

Process	lb Solids/lb BOD Removed
Primary	1.7
Activated sludge with primary	0.7
Activated sludge without primary	
Conventional	0.85
Step feed	0.85
Extended aeration	0.65
Oxidation ditch	0.65
Contact stabilization	1.0
Trickling filter	1.0
Rotating Biological contactor	1.0

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

The mass balance also provides an excellent mechanism to evaluate the validity of process control and effluent monitoring data generated. Table 18.7 lists average *K* factors in pounds of solids produced per pound of BOD removed for selected processes.

18.10.14.7.2.1 Conversion Factor

Conversion factors depend on the activated sludge modification involved. Factors generally range from 0.5 to 1.0 lb of solids/lb BOD removed (see Table 18.7).

18.10.14.7.2.2 Mass Balance Calculation

$$\text{BOD}_{in}\,(\text{lb}) = \text{BOD}_{in}\,(\text{mg/L}) \times \text{Q}\,(\text{MGD}) \times 8.34\ \text{lb/mg/L/MG}$$

$$\text{BOD}_{out}\,(\text{lb}) = \text{BOD}_{out}\,(\text{mg/L}) \times \text{Q}\,(\text{MGD}) \times 8.34\ \text{lb/mg/L/MG}$$

$$\text{Solids Produced}\,(\text{lb/d}) = \left[\text{BOD}_{in}\,(\text{lb}) - \text{BOD}_{out}\,(\text{lb})\right] \times \text{K}$$

$$\text{TSS}_{out}\,(\text{lb/d}) = \text{TSS}_{out}\,(\text{mg/L}) \times \text{Q}\,(\text{MGD}) \times 8.34\ \text{lb/mg/L/MG}$$

$$\text{Waste}\,(\text{lb/d}) = \text{Waste}\,(\text{mg/L}) \times \text{Q}\,(\text{MGD}) \times 8.34\ \text{lb/mg/L/MG}$$

$$\text{Solids Removed}\,(\text{lb/d}) = \text{TSS}_{out}\,(\text{lb/d}) + \text{Waste}\,(\text{lb/d})$$

$$\%\text{Mass Balance} = \frac{[\text{Solids Produced} - \text{Solids Removed}] \times 100}{\text{Solids Produced}} \tag{18.47}$$

18.10.14.7.2.3 Explanation of Results

If the mass balance is ±15%, the process sampling and testing and process control are within acceptable levels. If the balance is greater than15%, investigate further to determine if the discrepancy represents a process control problem or is the result of nonrepresentative sampling and inaccurate testing.

18.10.14.7.2.4 Sludge Waste Based upon Mass Balance

The mass balance calculation predicts the amount or sludge that will be produced by a treatment process. This information can then be used to determine what, under current operating conditions, that waste rate must be to maintain the current solids level.

$$\text{Waste Rate, MGD} = \frac{\text{Solids Produced, lb/d}}{(\text{Waste Concentration} \times 8.34\ \text{lb/gal})} \tag{18.44}$$

EXAMPLE 18.50

Problem:

Given the following data, determine the mass balance of the biological process and the appropriate waste rate to maintain current operating conditions:

Process	Extended Aeration (No Primary)	
Influent	Flow	1.1 MGD
	BOD	220 mg/L
	TSS	240 mg/L
Effluent	Flow	1.5 MGD
	BOD	18 mg/L
	TSS	22 mg/L
Waste	Flow	24,000 gal/d
	TSS	8710 mg/L

$$\text{BOD}_{in}\,(\text{lb/d}) = 220\ \text{mg/L} \times 1.1\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG} = 2018\ \text{lb/d}$$

$$\text{BOD}_{out}\,(\text{lb/d}) = 18\ \text{mg/L} \times 1.1\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG} = 165\ \text{lb/d}$$

$$\text{BOD Removed}\,(\text{lb/d}) = 2018\ \text{lb/d} - 165\ \text{lb/d} = 1853\ \text{lb/d}$$

$$\text{Solids Produced}\,(\text{lb/d}) = 1853\ \text{lb/d} \times 0.65\ \text{lb/lb BOD} = 1204\ \text{lb/d}$$

$$\text{Solids Out}\,(\text{lb/d}) = 22\ \text{mg/L} \times 1.1\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG} = 202\ \text{lb/d}$$

$$\text{Sludge Out}\,(\text{lb/d}) = 8710\ \text{mg/L} \times 0.024\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG} = 1743\ \text{lb/d}$$

$$\text{Solids Removed}\,(\text{lb/d}) = 292\ \text{lb/d} + 1743\ \text{lb/d} = 1945\ \text{lb/d}$$

$$\%\text{Mass Balance} = \frac{[1204\ \text{lb/d} - 1945\ \text{lb/d}] \times 100}{1204\ \text{lb/d}} = 62\%$$

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The mass balance indicates:

1. The sampling points, collection methods, and laboratory testing procedures are producing nonrepresentative results.
2. The process is removing significantly more solids than is required. Additional testing should be performed to isolate the specific cause of the imbalance.

To assist in the evaluation, the waste rate based upon the mass balance information can be calculated:

$$\text{Waste}\left(\text{gal/d}\right) = \frac{\text{Solids Produced}\left(\text{lb/d}\right)}{\text{Waste TSS}\left(\text{mg/L}\right)\times 8.34}$$

Using this equation results in the following:

$$\text{Waste}\left(\text{gal/d}\right) = \frac{1204\left(\text{lb/d}\right)\times 1{,}000{,}000}{8710\ \text{mg/L}\times 8.34}$$

$$= 16{,}575\ \text{gal/d}$$

18.10.15 Solids Concentration: Secondary Clarifier

The solids concentration in the secondary clarifier can be assumed to be equal to the solids concentration in the aeration tank effluent. It may also be determined in the laboratory using a core sample taken from the secondary clarifier. The secondary clarifier solids concentration can be calculated as an average of the secondary effluent suspended solids and the RAS suspended solids concentration.

18.10.16 Activated Sludge Process Record Keeping Requirements

Wastewater operators soon learn that record keeping is a major requirement and responsibility of their jobs. Records are essential for process control, providing information on the cause of problems, providing information for making seasonal changes, and compliance with regulatory agencies. Records should include sampling and testing data, process control calculations, meter readings, process adjustments, operational problems and corrective actions taken, and process observations.

18.11 DISINFECTION OF WASTEWATER

Like drinking water, liquid wastewater effluent is disinfected. Unlike drinking water, wastewater effluent is disinfected not to directly (direct end-of-pipe connection) protect a drinking water supply, but instead is treated to protect public health in general. This is particularly important when the secondary effluent is discharged into a body of water used for swimming or for a downstream water supply.

In the treatment of water for human consumption, treated water is typically chlorinated (although ozonation is also currently being applied in many cases). Chlorination is the preferred disinfection in potable water supplies because of chlorine's unique ability to provide a residual. This chlorine residual is important because when treated water leaves the waterworks facility and enters the distribution system, the possibility of contamination is increased. The residual works to continuously disinfect water right up to the consumer's tap.

In this section, we discuss basic chlorination and dechlorination. In addition, we describe UV irradiation, ozonation, bromine chlorine, and no disinfection. Keep in mind that much of the chlorination material presented here is similar to the information presented in Chapter 17, Water Treatment Operations and Unit Processes.

18.11.1 Chlorine Disinfection

Chlorination for disinfection, as shown in Figure 18.1, follows all other steps in conventional wastewater treatment. The purpose of chlorination is to reduce the population of organisms in the wastewater to levels low enough to ensure that pathogenic organisms will not be present in sufficient quantities to cause disease when discharged.

Note: Chlorine gas is heavier than air (vapor density of 2.5). Exhaust from a chlorinator room should be taken from floor level.

Note: The safest action to take in the event of a major chlorine container leak is to call the fire department.

Note: You might wonder why it is that chlorination of critical waters such as natural trout streams is not normal practice. This practice is strictly prohibited because chlorine and its by-products (i.e., chloramines) are extremely toxic to aquatic organisms.

18.11.1.1 Chlorination Terminology

Remember that there are several terms used in discussion of disinfection by chlorination. Because it is important for the operator to be familiar with these terms, we repeat key terms again.

Chlorine a strong oxidizing agent that has strong disinfecting capability. A yellow-green gas that is extremely corrosive and is toxic to humans in extremely low concentrations in air.

Contact time the length of time the time the disinfecting agent and the wastewater remain in contact.

Demand the chemical reactions that must be satisfied before a residual or excess chemical will appear.

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Disinfection the selective destruction of disease-causing organisms. All the organisms are not destroyed during the process. This differentiates disinfection from sterilization, which is the destruction of all organisms.

Dose the amount of chemical being added in milligrams per liter.

Feed rate the amount of chemical being added in pounds per day.

Residual the amount of disinfecting chemical remaining after the demand has been satisfied.

Sterilization the removal of all living organisms.

18.11.1.2 Wastewater Chlorination: Facts and Process Description

18.11.1.2.1 Chlorine Facts

1. Elemental chlorine (Cl_2 — gaseous) is a yellow-green gas, 2.5 times heavier than air.
2. The most common use of chlorine in wastewater treatment is for disinfection. Other uses include odor control and activated sludge bulking control. Chlorination takes place prior to the discharge of the final effluent to the receiving waters (see Figure 18.1).
3. Chlorine may also be used for nitrogen removal through a process called breakpoint chlorination. For nitrogen removal, enough chlorine is added to the wastewater to convert all the ammonium nitrogen gas. To do this, approximately 10 mg/L of chlorine must be added for every 1 mg/L of ammonium nitrogen in the wastewater.
4. For disinfection, chlorine is fed manually or automatically into a chlorine contact tank or basin, where it contacts flowing wastewater for at least 30 min to destroy disease-causing microorganisms (pathogens) found in treated wastewater.
5. Chorine may be applied as a gas, a solid, or liquid hypochlorite form.
6. Chorine is a very reactive substance. It has the potential to react with many different chemicals (including ammonia), as well as with organic matter. When chlorine is added to wastewater, several reactions occur:
   A. Chlorine will react with any reducing agent (i.e., sulfide, nitrite, iron, and thiosulfate) present in wastewater. These reactions are known as *chlorine demand.* The chlorine used for these reactions is not available for disinfection.
   B. Chlorine also reacts with organic compounds and ammonia compounds to form chlororganics and chloramines. Chloramines are part of the group of chlorine compounds that have disinfecting properties and show up as part of the chlorine residual test.
   C. After all of the chlorine demands are met, the addition of more chlorine will produce free residual chlorine. Producing free residual chlorine in wastewater requires very large additions of chlorine.

18.11.1.2.2 Hypochlorite Facts

Although there are some minor hazards associated with its use (e.g., skin irritation, nose irritation, and burning eyes), hypochlorite is relatively safe to work with. It is normally available in dry form as a white powder, pellet or tablet, or liquid form. It can be added directly using a dry chemical feeder or it can be dissolved and fed as a solution.

Note: In most wastewater treatment systems, disinfection is accomplished by means of combined residual.

18.11.1.2.3 Process Description

Chlorine is a very reactive substance. Chlorine is added to wastewater to satisfy all chemical demands (i.e., to react with certain chemicals such as sulfide, sulfite, ferrous iron, etc.). When these initial chemical demands have been satisfied, chlorine will react with substances, such as ammonia, to produce chloramines and other substances that, although not as effective as chlorine, have disinfecting capability. This produces a combined residual, which can be measured using residual chlorine test methods. If additional chlorine is added, free residual chlorine can be produced. Due to the chemicals normally found in wastewater, chlorine residuals are normally combined rather than free residuals. Control of the disinfection process is normally based upon maintaining total residual chlorine (TRC) of at least 1.0 mg/L for a contact time of at least 30 min at design flow.

Note: Residual level, contact time, and effluent quality affect disinfection. Failure to maintain the desired residual levels for the required contact time will result in lower efficiency and increased probability that disease organisms will be discharged.

Based on water quality standards, **total residual limitations** on chlorine are:

1. Fresh water — Less than 11 ppb total residual chlorine.
2. Estuaries — Less than 7.5 ppb for halogen produced oxidants.
3. Endangered species — Use of chlorine is prohibited.

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18.11.1.3 Chlorination Equipment

18.11.1.3.1 Hypochlorite Systems

Depending on the form of hypochlorite selected for use, special equipment that controls the addition of hypochlorite to the wastewater is required. Liquid forms require the use of metering pumps, which can deliver varying flows of hypochlorite solution. Dry chemicals require the use of a feed system designed to provide variable doses of the form used. The tablet form of hypochlorite requires the use of a tablet chlorinator designed specifically to provide the desired dose of chlorine. The hypochlorite solution or dry feed systems dispenses the hypochlorite, which is then mixed with the flow. The treated wastewater then enters the contact tank to provide the required contact time.

18.11.1.3.2 Chlorine Systems

Because of the potential hazards associated with the use of chlorine, the equipment requirements are significantly greater than those associated with hypochlorite use. The system most widely used is a solution feed system. In this system, chlorine is removed from the container at a flow rate controlled by a variable orifice. Water moving through the chlorine injector creates a vacuum that draws the chlorine gas to the injector and mixes it with the water. The chlorine gas reacts with the water to form hypochlorous and hydrochloric acid. The solution is then piped to the chlorine contact tank and dispersed into the wastewater through a diffuser. Larger facilities may withdraw the liquid form of chlorine and use evaporators (heaters) to convert to the gas form. Small facilities will normally draw the gas form of chlorine from the cylinder. As gas is withdrawn liquid will be converted to the gas form. This requires heat energy and may result in chlorine line freeze-up if the withdrawal rate exceeds the available energy levels.

18.11.1.4 Chlorination: Operation

In both the hypochlorite and chlorine systems normal operation requires adjustment of feed rates to ensure the required residual levels are maintained. This normally requires chlorine residual testing and adjustment based upon the results of the test. Other activities include the removal of accumulated solids from the contact tank, collection of bacteriological samples to evaluate process performance, and maintenance of safety equipment (respirator air pack, safety lines, etc.).

Hypochlorite operation may also include makeup solution (solution feed systems), adding powder or pellets to the dry chemical feeder or tablets to the tablet chlorinator.

Chlorine operations include the adjustment of chlorinator feed rates, inspection of mechanical equipment, testing for leaks using an ammonia swab (white smoke indicates leaks), changing containers (requires more than one person for safety), and adjusting the injector water feed rate when required.

Chlorination requires routine testing of plant effluent for TRC and may also require the collection and analysis of samples to determine the fecal coliform concentration in the effluent.

18.11.1.5 Troubleshooting Operational Problems

Operational problems with the plant's disinfection process occasionally develop. The wastewater operator must not only be able to recognize these problems, but also correct them. For proper operation, the chlorination process requires routine observation, meter readings, process control and testing, and various process control calculations. Comparison of daily results with expected normal ranges is the key to identifying problems during the troubleshooting process and taking appropriate corrective actions (if required).

In this section, we review normal operational and performance factors. We point out the various problems that can occur with the plant's disinfection process, the causes, and the corrective actions that should be taken.

18.11.1.5.1 Operator Observations

The operator should consider the following items:

1. Flow distribution — The operator monitors the flow to ensure that it is evenly distributed between all units in service, and that the flow through each individual unit is uniform, with no indication of short-circuiting.
2. Contact tank — The contact tanks or basins must be checked to ensure that no excessive accumulation of scum is on the surface, no indication of solids accumulation is on the bottom, and mixing appears to be adequate.
3. Chlorinator — The operator should check to ensure that there is no evidence of leakage, operating pressure or vacuum is within specified levels, current chlorine feed settling is within expected levels, in-line cylinders have sufficient chlorine to ensure continuous feed, and the exhaust system is operating as designed.

18.11.1.5.1.1 Factors Affecting Performance

Operators must be familiar with those factors that affect chlorination performance. Any item that interferes with the chlorine reactions or increases the demand for chlorine can affect performance and may produce nondisinfectant products. We discuss the main factors affecting chlorination performance below:

1. Effluent quality — Poor quality effluents have higher chlorine demands. In addition, high concentrations of solids prevent chlorine-organism

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contact, and incomplete nitrification can cause extremely high chlorine demand.

2. Mixing — In order to be effective, chlorine must be in contact with the organisms. Poor mixing results in poor chlorine distribution. Installing of baffles and using a high length-to-width ratio will improve mixing and contact.
3. Contact time — The chlorine disinfection process is time dependent. As the contact time decreases, process effectiveness decreases. A minimum of 30 min of contact must be available at design flow.
4. Residual levels — The chlorine disinfection process is TRC dependent. The concentration of residual must be sufficient to ensure the desired reactions occur. At the design contact time, the required minimum TRC concentration is 1.0 mg/L.

18.11.1.5.1.2 Process Control Sampling and Testing

To ensure proper operation of the chlorination process, the operator must perform process control testing for the chlorination process. (Note: The process performance evaluation is based on the bacterial content (fecal coliform) of the final effluent.) Process control testing consists of performing a *total chlorine residual test* on chlorine contact effluent. The frequency of the testing is specified in the plant permit. The normal expected range of results is also specified in the plant permit.

18.11.1.5.1.3 Troubleshooting

The following sections present common operational problems, symptoms, casual factors, and corrective actions associated with chlorination system use in wastewater treatment.

1. Symptom 1: Coliform count fails to meet required standards for disinfection.
   A. Cause: Inadequate chlorination equipment capacity.
      Corrective action: Replace equipment as necessary to provide treatment based on maximum flow through the pipe.
   B. Cause: Inadequate chlorine residual control.
      Corrective action: Use chlorine residual analyzer to monitor and control chlorine dosage automatically.
   C. Cause: Short circuiting in chlorine contact chamber.
      Corrective action: Install baffling in the chlorine contact chamber. Install mixing device in chlorine contact chamber.
   D. Cause: Solids buildup in contact chamber.
      Corrective action: Clean contact chamber.
   E. Cause: Chlorine residual is too low.
      Corrective action: Increase contact time or increase chlorine feed rate.
2. Symptom 2: Low chlorine gas pressure at the chlorinator.
   A. Cause: Insufficient number of cylinders connected to the system.
      Corrective action: Connect enough cylinders to system so that feed rate does not exceed recommended withdrawal rate for cylinders.
   B. Cause: Stoppage or restriction of flow between cylinders and chlorinator.
      Corrective action: Disassemble chlorine header system at point where cooling begins, locate stoppage, and clean with solvent.
3. Symptom 3: No chlorine gas pressure at the chlorinator.
   A. Cause: Chlorine cylinders empty or not connected to the system.
      Corrective action: Connect cylinders or replace empty cylinders.
   B. Cause: Plugged or damaged pressure reducing valve.
      Corrective action: Repair reducing valve after shutting cylinder valves and decreasing gas in the header system.
4. Symptom 4: Chlorinator will not feed any chlorine.
   A. Cause: Pressure reducing valve in chlorinator is dirty.
      Corrective action: Disassemble chlorinator and clean valve stem and seat. Precede valve with filter or sediment trap.
   B. Cause: Chlorine cylinder is hotter than chlorine control apparatus (chlorinator).
      Corrective action: Reduce temperature in cylinder area; do not connect a new cylinder, which has been sitting in the sun.
5. Symptom 5: Chlorine gas escaping from the chlorine pressure reducing valve (CPRV).
   A. Cause: Main diaphragm of CPRV has ruptured.
      Corrective action: Disassemble valve and diaphragm. Inspect chlorine supply system for moisture intrusion.
6. Symptom 6: Inability to maintain chlorine feed rate without icing of chlorine system.
   A. Cause: Insufficient evaporator capacity.
      Corrective action: Reduce feed rate to 75% of evaporator capacity. If this eliminates problem, then main diaphragm of CPRV is ruptured.
   B. Cause: External CPRV cartridge is clogged.
      Corrective action: Flush and clean cartridge.

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7. Symptom 7: Chlorinator system is unable to maintain sufficient water bath temperature to keep external CPRV open.
   A. Cause: Heating element malfunction.
      Corrective action: Remove and replace heating element.
8. Symptom 8: Inability to obtain maximum feed rate from chlorinator.
   A. Cause: Inadequate chlorine gas pressure.
      Corrective action: Increase pressure and replace empty or low cylinders.
   B. Cause: Water pump injector clogged with deposits.
      Corrective action: Clean injector parts using muriatic acid. Rinse parts with fresh water and place back in service.
   C. Cause: Leak in vacuum relief valve.
      Corrective action: Disassemble vacuum relief valve and replace all springs.
   D. Cause: Vacuum leak in joints, gaskets, tubing, etc. in chlorinator system.
      Corrective action: Repair all vacuum leaks by tightening joints, replacing gaskets, and replacing tubing and compression nuts.
9. Symptom 9: Inability to maintain adequate chlorine feed rate.
   A. Cause: Malfunction or deterioration of chlorine water supply pump.
      Corrective action: Overhaul pump (if turbine pump is used, try closing valve to maintain proper discharge pressure).
10. Symptom 10: Chlorine residual too high in plant effluent to meet requirements.
    A. Cause: Chlorine residual too high
       Corrective action: Install dechlorination facilities.
11. Symptom 11: Wide variation in chlorine residual produced in the effluent.
    A. Cause: Chlorine flow proportion meter capacity inadequate to meet plant flow rates.
       Corrective action: Replace with higher capacity chlorinator meter.
    B. Cause: Malfunctioning controls.
       Corrective action: Call manufacturer technical representative.
    C. Cause: Solids settled in chlorine contact chamber.
       Corrective action: Clean chlorine contact tank.
    D. Cause: Flow proportioning control device not zeroed or spanned correctly
       Corrective action: Rezero and span the device in accordance with manufacturer's instructions.
12. Symptom 12: Unable to obtain chlorine residual.
    A. Cause: High chemical demand.
       Corrective action: Locate and correct the source of the high demand.
    B. Cause: Test interference.
       Corrective action: Add sulfuric acid to samples to reduce interference.
13. Symptom 13: Chlorine residual analyzer, recorder, and controller does not control chlorine residual properly.
    A. Cause: Electrodes fouled.
       Corrective action: Clean electrodes.
    B. Cause: Loop time is too long.
       Corrective actions: Reduce control loop time by:
       1. Moving the injector closer to the point of application.
       2. Increasing the velocity in the sample line to the analyzer.
       3. Moving the cell closer to the sample point.
       4. Moving the sample point closer to the point of application.
    C. Cause: Insufficient potassium iodide being added for the amount of residual being measured.
       Corrective action: Adjust potassium iodide feed to correspond with the chlorine residual being measured.
    D. Cause: Buffer additive system is malfunctioning.
       Corrective action: Repair buffer additive system.
    E. Cause: Malfunctioning of analyzer cell.
       Corrective action: Call authorized service personnel to repair electrical components.
    F. Cause: Poor mixing of chlorine at point of application.
       Corrective action: Install mixing device to cause turbulence at point of application.
    G. Cause: Rotameter tube range is improperly set.
       Corrective action: Replace rotameter with a proper range of feed rate.

18.11.1.6 Dechlorination

The purpose of dechlorination is to remove chlorine and reaction products (chloramines) before the treated wastestream is discharged into its receiving waters. Dechlorination follows chlorination, usually at the end of the contact tank to the final effluent. Sulfur dioxide gas, sodium sulfate, sodium metabisulfate, or sodium bisulfates are the chemicals used to dechlorinate. No matter which chemical is used to dechlorinate, its reaction with chlorine is instantaneous.

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18.11.1.7 Chlorination Environmental Hazards and Safety

Chlorine is an extremely toxic substance that can cause severe damage when released to the environment. For this reason, most state regulatory agencies have established a chlorine water quality standard (e.g., in Virginia, 0.011 mg/L in fresh waters for TRC and 0.0075 mg/L for chlorine produced oxidants in saline waters). Studies have indicated that quantities above these levels chlorine can reduce shellfish growth and destroy sensitive aquatic organisms. This standard has resulted in many treatment facilities being required to add an additional process to remove the chlorine prior to discharge. As mentioned, the process, known as dechlorination, uses chemicals that react quickly with chlorine to convert it to a less harmful form.

Elemental chlorine is a chemical with potentially fatal hazards associated with it. For this reason many different state and federal agencies regulate the transport, storage, and use of chlorine. All operators required to work with chlorine should be trained in proper handling techniques. They should also be trained to ensure that all procedures for storage transport, handling and use of chlorine are in compliance with appropriate state and federal regulations.

18.11.1.8 Chlorine: Safe Work Practice

Because of the inherent dangers involved with handling chlorine, each facility using chlorine (for any reason) should ensure that a written safe work practice is in place and is followed by plant operators. A sample safe work practice for handling chlorine is provided below.

Work: Chemical Handling: Chlorine

Practice

1. Plant personnel must be trained and instructed on the use and handling of chlorine, chlorine equipment, chlorine emergency repair kits, and other chlorine emergency procedures.
2. Use extreme care and caution when handling chlorine.
3. Lift chlorine cylinders only with an approved and load-tested device.
4. Secure chlorine cylinders into position immediately. Never leave a cylinder suspended.
5. Avoid dropping chlorine cylinders.
6. Avoid banging chlorine cylinders into other objects.
7. Store chlorine 1-ton cylinders in a cool dry place away from direct sunlight or heating units. Railroad tank cars are direct sunlight compensated.
8. Store chlorine 1-ton cylinders on their sides only (horizontally).
9. Do not stack unused or used chlorine cylinders.
10. Provide positive ventilation to the chlorine storage area and chlorinator room.
11. *Always* keep chlorine cylinders at ambient temperature. *Never* apply direct flame to a chlorine cylinder.
12. Use the oldest chlorine cylinder in stock first.
13. Always keep valve protection hoods in place until the chlorine cylinders are ready for connection.
14. Except to repair a leak, do not tamper with the fusible plugs on chlorine cylinders.
15. Wear a self-contained breathing apparatus (SCBA) whenever changing a chlorine cylinder and have at least one other person with a standby SCBA unit outside the immediate area.
16. Inspect all threads and surfaces of a chlorine cylinder, and have at least one other person with a standby SCBA unit outside the immediate area.
17. Use new lead gaskets each time a chlorine cylinder connection is made.
18. Use only the specified wrench to operate chlorine cylinder valves.
19. Open chlorine cylinder valves slowly (no more than one full turn).
20. Do not hammer, bang, or force chlorine cylinder valves under any circumstances.
21. Check for chlorine leaks as soon as the chlorine cylinder connection is made. Leaks are checked for by gently expelling ammonia mist from a plastic squeeze bottle filled with approximately 2 oz of liquid ammonia solution. Do not put liquid ammonia on valves or equipment.
22. Correct all minor chlorine leaks at the chlorine cylinder connection immediately.
23. Except for automatic systems, draw chlorine from only one manifolded chlorine cylinder at a time. *Never* simultaneously open two or more chlorine cylinders connected to a common manifold pulling liquid chlorine. Two or more cylinders connected to a common manifold pulling gaseous chlorine are acceptable.
24. Wear SCBA and chemical protective clothing covering face, arms, and hands before entering an enclosed chlorine area to investigate a chlorine odor or chlorine leak (two-person rule required).
25. Provide positive ventilation to a contaminated chlorine atmosphere before entering whenever possible.
26. Have at least two personnel present before entering a chlorine atmosphere. One person should enter the chlorine atmosphere, and the other should observe in the event of an emergency. Never enter a chlorine atmosphere unattended.

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Remember that the Occupational Safety and Health Administration (OSHA) mandates that only fully qualified Level III hazardous material (HAZMAT) responders are authorized to aggressively attack a HAZMAT leak such as chlorine.

27. Use supplied-air-breathing equipment when entering a chlorine atmosphere. Never use canister-type gas masks when entering a chlorine atmosphere.
28. Ensure that all supplied air-breathing apparatuses have been properly maintained in accordance with the plant's SCBA inspection guidelines as specified in the plant's respiratory protection program.
29. Stay upwind from all chlorine leak danger areas unless involved with making repairs. Look to plant windsocks for wind direction.
30. Contact trained plant personnel to repair chlorine leaks.
31. Roll uncontrollable leaking chlorine cylinders so that the chlorine escapes as a gas, not as a liquid.
32. Stop leaking chlorine cylinders or leaking chlorine equipment (by closing off valves if possible) prior to attempting repair.
33. Connect uncontrollable leaking chlorine cylinders to the chlorination equipment and feed the maximum chlorine feed rate possible.
34. Keep leaking chlorine cylinders at the plant site. Chlorine cylinders received at the plant site must be inspected for leaks prior to taking delivery from the shipper. Never ship a leaking chlorine cylinder back to the supplier after it has been accepted (bill of lading has been signed by plant personnel) from the shipper. Instead, repair or stop the leak first.
35. Keep moisture away from a chlorine leak. Never put water onto a chlorine leak.
36. Call the fire department or rescue squad if a person is incapacitated by chlorine.
37. Administer cardiopulmonary resuscitation (use barrier mask if possible) immediately to person who has been incapacitated by chlorine.
38. Breathe shallow rather than deep if exposed to chlorine without the appropriate respiratory protection.
39. Place a person who does not have difficulty breathing and is heavily contaminated with chlorine into a deluge shower. Remove their clothing under the water and flush all body parts that were exposed to chlorine.
40. Flush eyes contaminated with chlorine with copious quantities of lukewarm running water for at least 15 min.
41. Drink milk if throat is irritated by chlorine.
42. Never store other materials in chlorine cylinder storage areas. Substances like acetylene and propane are not compatible with chlorine.

18.11.1.9 Chlorination Process Calculations

There are several calculations that may be useful in operating a chlorination system. Many of these calculations are discussed and illustrated in this section.

18.11.1.9.1 Chlorine Demand

Chlorine demand is the amount of chlorine in milligrams per liter that must be added to the wastewater to complete all of the chemical reactions that must occur prior to producing a residual:

$$\text{Chlorine Demand} = \text{Chlorine Dose}\ (\text{mg/L}) - \text{Chlorine Residual}\ (\text{mg/L}) \tag{18.48}$$

Example 18.51

Problem:

The plant effluent currently requires a chlorine dose of 7.1 mg/L to produce the required 1.0 mg/L chlorine residual in the chlorine contact tank. What is the chlorine demand in milligrams per liter?

Solution:

$$\text{Chlorine Demand}\ (\text{mg/L}) = 7.1\ \text{mg/L} - 1.0\ \text{mg/L} = 6.1\ \text{mg/L}$$

18.11.1.9.2 Chlorine Feed Rate

Chlorine feed rate is the amount of chlorine added to the wastewater in pounds per day:

$$\text{Chlorine Feed Rate} = \text{Dose}\ (\text{mg/L}) \times \text{Q (MGD)} \times 8.34\ \text{lb/mg/L/MG} \tag{18.49}$$

Example 18.52

Problem:

The current chlorine dose is 5.55 mg/L. What is the feed rate in pounds per day if the flow is 22.89 MGD?

Solution:

$$\text{Chlorine Feed Rate}\ (\text{lb/d}) = 5.55\ \text{mg/L} \times 22.89\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG} = 1060\ \text{lb/d}$$

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18.11.1.9.3 Chlorine Dose

Chlorine dose is the concentration of chlorine being added to the wastewater. It is expressed in milligrams per liter:

$$\text{Dose}\ (\text{mg/L}) = \frac{\text{Chlorine Feed Rate}\ (\text{lb/d})}{\text{Q}\ (\text{MGD}) \times 8.34\ \text{lb/mg/L/MG}} \quad (18.50)$$

EXAMPLE 18.53

Problem:

Three hundred twenty pounds of chlorine are added per day to a wastewater flow of 5.6 MGD. What is the chlorine does in milligrams per liter?

Solution:

$$\text{Dose}\ (\text{mg/L}) = \frac{320\ \text{lb/d}}{5.6\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}}$$

$$= 6.9\ \text{mg/L}$$

18.11.1.9.4 Available Chlorine

When hypochlorite forms of chlorine are used, the available chlorine is listed on the label. In these cases, the amount of chemical added must be converted to the actual amount of chlorine using the following calculation:

$$\text{Available Chlorine} = \text{Amount of Hypochlorite} \times \text{\% Available Chlorine} \quad (18.51)$$

EXAMPLE 18.54

Problem:

The calcium hypochlorite used for chlorination contains 62.5% available chlorine. How many pounds of chlorine are added to the plant effluent if the current feed rate is 30 lb of calcium hypochlorite per day?

Solution:

$$\text{Available Chlorine} = 30\ \text{lb} \times 0.625$$

$$= 18.75\ \text{lb Chlorine}$$

18.11.1.9.5 Required Quantity of Dry Hypochlorite

Use Equation 18.64 to determine the amount of hypochlorite needed to achieve the desired dose of chlorine:

$$\text{Hypochlorite Quantity}\ (\text{lb/d}) = \frac{\text{Required Chlorine Dose}\ (\text{mg/L}) \times \text{Q}\ (\text{MGD}) \times 8.34\ \text{lg/mg/L/MG}}{\text{\%Available Chlorine}} \quad (18.52)$$

EXAMPLE 18.55

Problem:

The laboratory reports that the chlorine dose required to maintain the desired residual level is 8.5 mg/L. Today's flow rate is 3.25 MGD. The hypochlorite powder used for disinfection is 70% available chlorine. How many pounds of hypochlorite must be used?

Solution:

$$\text{Hypochlorite Quantity}\ (\text{lb/d})$$

$$= \frac{8.5\ \text{mg/L} \times 3.25\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}}{0.70}$$

$$= 329\ \text{lb/d}$$

18.11.1.9.6 Required Quantity of Liquid Hypochlorite

Use Equation 18.65 to calculate the required quantity of liquid hypochlorite:

$$\text{Hypochlorite Quantity}\ (\text{gal/d}) = \text{Required Chlorine Dose}\ (\text{mg/L}) \times \text{Q}\ (\text{MGD}) \times \frac{8.34\ \text{lb/mg/L/MG}}{\text{\%Available Chlorine} \times 8.34\ \text{lb/gal} \times \text{Hypochlorite Solution Specific Gravity}} \quad (18.53)$$

EXAMPLE 18.56

Problem:

The chlorine dose is 8.8 mg/L and the flow rate is 3.28 MGD. The hypochlorite solution is 71% available chlorine and has a specific gravity of 1.25. How many pounds of hypochlorite must be used?

$$\text{Hypochlorite Quantity}\ (\text{gal/d})$$

$$= \frac{8.8\ \text{mg/L} \times 3.28\ \text{MGD} \times 8.34\ \text{lb/mg/L/MG}}{0.71 \times 8.34\ \text{lb/gal} \times 1.25}$$

$$= 32.5\ \text{gal/d}$$

18.11.1.9.7 Chlorine Ordering

Because disinfection must be continuous, the supply of chlorine must never be allowed to run out. The following calculation provides a simple method for determining when additional supplies must be ordered. The process consists of three steps:

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1. Adjust the flow and use variations if projected changes are provided.
2. If an increase in flow or required dosage is projected, the current flow rate or dose must be adjusted to reflect the projected change.
3. Use the following equation:

$$\begin{aligned}\text{Projected Flow} &= \text{Current Flow (MGD)} \times [1.0 + \%\text{Change}] \\ \text{Projected Dose} &= \text{Current Dose (mg/L)} \times [1.0 + \%\text{Change}]\end{aligned} \tag{18.54}$$

Example 18.57

Problem:

Based on available information for the past 12 months, the operator projects that the effluent flow rate will increase by 7.5% during the next year. If the average daily flow has been 4.5 MGD, what will be the projected flow for the next 12 months?

Solution:

$$\begin{aligned}\text{Projected Flow (MGD)} &= 4.5 \text{ MGD} \times [1.0 + 0.075] \\ &= 4.84 \text{ MGD}\end{aligned}$$

Example 18.58

Problem:

The plant currently uses 90 lb of chlorine/d. The town wishes to order enough chlorine to supply the plant for 3 months (assume 31 d/month). How many pounds of chlorine should be ordered to provide the needed supply?

Solution:

Determine the amount of chlorine required for a given period:

$$\begin{aligned}\text{Chlorine Required} &= \text{Feed Rate (lb/d)} \times \text{Number of Days Required} \\ &= 90 \text{ lb/d} \times 124 \text{ d} \\ &= 11{,}160 \text{ lb}\end{aligned}$$

Note: In some instances, projections for flow or dose changes are not available, but the plant operator may wish to include an extra amount of chlorine as a safety factor. This safety factor can be stated as a specific quantity or as a percentage of the projected usage. Safety factor as a specific quantity can be expressed as follows:

$$\text{Total Required } Cl_2 = \text{Chlorine Required (lb)} + \text{Safety Factor}$$

Note: Chlorine is only shipped in full containers. Unless you specifically ask for the amount of chlorine actually required or used during a specified period, all decimal parts of a cylinder are rounded up to the next highest number of full cylinders.

18.11.2 UV Irradiation

Although ultraviolet disinfection was recognized as a method for achieving disinfection in the late nineteenth century, its application virtually disappeared with the evolution of chlorination technologies. However, in recent years, there has been resurgence in its use in the wastewater field, largely as a consequence of concern for discharge of toxic chlorine residual. Even more recently, UV has gained more attention because of the tough new regulations on chlorine use imposed by both OSHA and EPA. Because of this relatively recent increased regulatory pressure, many facilities are actively engaged in substituting chlorine for other disinfection alternatives. UV technology has made many improvements, making UV attractive as a disinfection alternative.

UV light has very good germicidal qualities and is very effective in destroying microorganisms. It is used in hospitals, biological testing facilities, and many other similar locations. In wastewater treatment, the plant effluent is exposed to ultraviolet light of a specified wavelength and intensity for a specified contact period. The effectiveness of the process is dependent upon

1. UV light intensity
2. Contact time
3. Wastewater quality (turbidity)

The Achilles' heel of UV for disinfecting wastewater is turbidity. If the wastewater quality is poor, the ultraviolet light will be unable to penetrate the solids and the effectiveness of the process decreases dramatically. For this reason, many states limit the use of UV disinfection to facilities that can reasonably be expected to produce an effluent containing less than or equal to 30 mg/L of BOD and TSS.

In the operation of UV systems, UV lamps must be readily available when replacements are required. The best lamps are those with a stated operating life of at least 7500 h that do not produce significant amounts of ozone or hydrogen peroxide. The lamps must also meet technical

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specifications for intensity, output, and arc length. If the UV light tubes are submerged in the wastestream, they must be protected inside quartz tubes. These tubes not only protect the lights, but also make cleaning and replacement easier.

Contact tanks must be used with UV disinfection. They must be designed with the banks of UV lights in a horizontal position that is either parallel or perpendicular to the flow or with banks of lights placed in a vertical position perpendicular to the flow.

Note: The contact tank must provide a minimum of 10 sec of exposure time.

We stated earlier that turbidity problems have been the main hinderance with using UV in wastewater treatment. If turbidity is UV's Achilles' heel, then the need for increased maintenance (as compared to other disinfection alternatives) is the toe of the same foot.

UV maintenance requires that the tubes be cleaned on a regular basis or as needed. In addition, periodic acid washing is also required to remove chemical buildup.

In operating UV disinfection systems, routine monitoring is required. Monitoring to check on bulb burnout, buildup of solids on quartz tubes, and UV light intensity is required.

Note: UV light is extremely hazardous to the eyes. Never enter an area where UV lights are in operation without proper eye protection. Never look directly into the UV light.

18.11.3 Ozonation

Ozone is a strong oxidizing gas that reacts with most organic and many inorganic molecules. It is produced when oxygen molecules separate, collide with other oxygen atoms, and form a molecule consisting of three oxygen atoms. For high-quality effluents, ozone is a very effective disinfectant. Current regulations for domestic treatment systems limit use of ozonation to filtered effluents unless the system's effectiveness can be demonstrated prior to installation.

Note: Effluent quality is the key performance factor for ozonation.

For ozonation of wastewater, the facility must have the capability to generate pure oxygen along with an ozone generator. A contact tank with greater than or equal to 10-min contact time at design average daily flow is required. Off-gas monitoring for process control is also required. In addition, safety equipment capable of monitoring ozone in the atmosphere and a ventilation system capable of preventing ozone levels exceeding 0.1 ppm is required.

The actual operation of the ozonation process consists of monitoring and adjusting the ozone generator and monitoring the control system to maintain the required ozone concentration in the off-gas. The process must also be evaluated periodically using biological testing to assess its effectiveness.

Note: Ozone is an extremely toxic substance. Concentrations in air should not exceed 0.1 ppm. It also has the potential to create an explosive atmosphere. Sufficient ventilation and purging capabilities should be provided.

Ozone has certain advantages over chlorine for disinfection of wastewater: (1) it increases DO in the effluent, (2) it has a briefer contact time, (3) it has no undesirable effects on marine organisms, and (4) it decreases turbidity and odor.

18.11.4 Bromine Chloride

Bromine chloride is a mixture of bromine and chlorine. It forms hydrocarbons and hydrochloric acid when mixed with water. Bromine chloride is an excellent disinfectant that reacts quickly and normally does not produce any long-term residuals.

Note: Bromine chloride is an extremely corrosive compound in the presence of low concentrations of moisture.

The reactions occurring when bromine chloride is added to the wastewater are similar to those occurring when chlorine is added. The major difference is the production of bromamine compounds rather than chloramines. The bromamine compounds are excellent disinfectants, but are less stable and dissipate quickly. In most cases, the bromamines decay into other, less toxic compounds rapidly and are undetectable in the plant effluent.

The factors that affect performance are similar to those affecting the performance of the chlorine disinfection process. Such factors as effluent quality and contact time have a direct impact on the performance of the process.

18.11.5 No Disinfection

In a very limited number of cases, treated wastewater discharges without disinfection is permitted. These are approved on a case-by-case basis. Each request must be evaluated based upon the point of discharge, the quality of the discharge, the potential for human contact, and many other factors.

18.12 ADVANCED WASTEWATER TREATMENT

Advanced wastewater treatment is defined as the methods and processes that remove more contaminants (suspended and dissolved substances) from wastewater than are taken

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out by conventional biological treatment. In other words, advanced wastewater treatment is the application of a process or system that follows secondary treatment or that includes phosphorus removal or nitrification in conventional secondary treatment.

Advanced wastewater treatment is used to augment conventional secondary treatment because secondary treatment typically removes only between 85 and 95% of the BOD and TSS in raw sanitary sewage. Generally, this leaves 30 mg/L or less of BOD and TSS in the secondary effluent. To meet stringent water-quality standards, this level of BOD and TSS in secondary effluent may not prevent violation of water-quality standards — the plant may not make permit. Thus, advanced wastewater treatment is often used to remove additional pollutants from treated wastewater.

In addition to meeting or exceeding the requirements of water-quality standards, treatment facilities use advanced wastewater treatment for other reasons as well. For example, conventional secondary wastewater treatment is sometimes not sufficient to protect the aquatic environment. This is the case when periodic flow events occur in a stream; the stream may not provide the amount of dilution of effluent needed to maintain the necessary DO levels for aquatic organism survival.

Secondary treatment has other limitations. It does not significantly reduce the effluent concentration of nitrogen and phosphorus (important plant nutrients) in sewage. If discharged into lakes, these nutrients contribute to algal blooms and accelerated eutrophication (lake aging). Also, the nitrogen in the sewage effluent may be present mostly in the form of ammonia compounds. If in high enough concentration, ammonia compounds are toxic to aquatic organisms. Yet another problem with these compounds is that they exert a nitrogenous oxygen demand in the receiving water as they convert to nitrates. This process is called nitrification.

Note: The term tertiary treatment is commonly used as a synonym for advanced wastewater treatment. These two terms do not have precisely the same meaning. Tertiary suggests a third step that is applied after primary and secondary treatment.

Advanced wastewater treatment can remove more than 99% of the pollutants from raw sewage and can produce an effluent of almost potable (drinking) water quality. However, advanced treatment is not free. The cost of advanced treatment for operation and maintenance as well as for retrofit of present conventional processes is very high (sometimes doubling the cost of secondary treatment). A plan to install advanced treatment technology calls for careful study; the benefit-to-cost ratio is not always big enough to justify the additional expense.

Even considering the expense, application of some form of advanced treatment is not uncommon. These treatment processes can be physical, chemical, or biological. The specific process used is based upon the purpose of the treatment and the quality of the effluent desired.

18.12.1 Chemical Treatment

The purpose of chemical treatment is to remove:

1. BOD
2. TSS
3. Phosphorus
4. Heavy metals
5. Other substances that can be chemically converted to a settleable solid

Chemical treatment is often accomplished as an add-on to existing treatment systems or by means of separate facilities specifically designed for chemical addition. In each case, the basic process necessary to achieve the desired results remains the same:

1. Chemicals are thoroughly mixed with the wastewater.
2. The chemical reactions that occur form solids (coagulation).
3. The solids are mixed to increase particle size (flocculation).
4. Settling and filtration (separation) remove the solids.

The specific chemical used depends on the pollutant to be removed and the characteristics of the wastewater. Chemicals may include the following:

1. Lime
2. Alum (aluminum sulfate)
3. Aluminum salts
4. Ferric or ferrous salts
5. Polymers
6. Bioadditives

18.12.1.1 Operation, Observation, and Troubleshooting Procedures

Operation and observation of performance of chemical treatment processes are dependent on the pollutant being removed and process design.

Operational problems associated with chemical treatment processes used in advanced treatment usually revolve around problems with floc formation, settling characteristics, removal in the settling tank, and sludge (in settling tank) turning anaerobic.

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To correct these problems, the operator must be able to recognize the applicable problem indicators through proper observation. Below we list common indicators and observations of operational problems, along with the applicable causal factors and corrective actions:

1. Poor floc formation and settling characteristics.
   A. Causal factors:
      1. Insufficient chemical dispersal during rapid mix.
      2. Excessive detention time in rapid mix.
      3. Improper coagulant dosage.
      4. Excessive flocculator speed.
   B. Corrective actions (where applicable):
      1. Increase speed of rapid mixer.
      2. Reduce detention time to15–60 sec.
      3. Correct dosage (determine by jar testing).
      4. Reduce flocculator speed.
2. Good floc formation, poor removal in settling tank.
   A. Causal factors:
      1. Excessive velocity between flocculation and settling.
      2. Settling tank operational problem.
   B. Corrective action:
      1. Reduce velocity to acceptable range
3. Settling tank sludge is turning anaerobic.
   A. Causal factors:
      1. A sludge blanket has developed in settling tank.
      2. Excessive organic carryover from secondary treatment.
   B. Corrective actions:
      1. Increase sludge withdrawal to eliminate blanket.
      2. Correct secondary treatment operational problems.

18.12.2 Microscreening

Microscreening (also called microstraining) is an advanced treatment process used to reduce suspended solids. The microscreens are composed of specially woven steel wire fabric mounted around the perimeter of a large revolving drum. The steel wire cloth acts as a fine screen, with openings as small as 20 μm (or millionths of a meter) that are small enough to remove microscopic organisms and debris.

The rotating drum is partially submerged in the secondary effluent, which must flow into the drum then outward through the microscreen. As the drum rotates, captured solids are carried to the top where a high-velocity water spray flushes them into a hopper or backwash tray mounted on the hollow axle of the drum. Backwash solids are recycled to plant influent for treatment. These units have found greatest application in treatment of industrial waters and final polishing filtration of wastewater effluents. Expected performance for suspended solids removal is 95 to 99%, but the typical suspended solids removal achieved with these units is about 55%. The normal range is from 10 to 80%.

According to Metcalf & Eddy[2], the functional design of the microscreen unit involves the following considerations:

1. The characterization of the suspended solids with respect to the concentration and degree of flocculation
2. The selection of unit design parameter values that will not only ensure capacity to meet maximum hydraulic loadings with critical solids characteristics, but also provide desired design performance over the expected range of hydraulic and solids loadings
3. The provision of backwash and cleaning facilities to maintain the capacity of the screen.

18.12.2.1 Operation, Observation, and Troubleshooting Procedures

Microscreen operators typically perform sampling and testing on influent and effluent TSS and monitor screen operation to ensure proper operation. Operational problems generally consist of gradual decrease in throughput rate, leakage at ends of the drum, reduced screen capacity, hot or noisy drive systems, erratic drum rotation, and sudden increases in effluent solids:

1. Decrease in throughput rate (from slime growth).
   A. Causal factors:
      1. Inadequate cleaning.
      2. Spray nozzles plugged.
   B. Corrective actions (where applicable):
      1. Increase backwash pressure (60 to 120 psi).
      2. Add hypochlorite upstream of the unit.
      3. Unclog nozzles.
2. Decreased performance from leakage at ends of the drum.
   A. Causal factor:
      1. Defective or leaking units.
   B. Corrective actions:
      1. Tighten tension on sealing bands.
      2. Replace sealing bands if excessive tension is required.
3. Screen capacity is reduced after shutdown period.
   A. Causal factor:
      1. Screen is fouled.
   B. Corrective actions:
      1. Clean screen prior to shutdown.
      2. Clean screen with hypochlorite.

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4. Drive System is running hot or noisy.
   A. Causal factor:
      1. Inadequate lubrication.
   B. Corrective action:
      1. Fill to specified level with recommended oil.
5. Erratic drum rotation.
   A. Causal factors:
      1. Improper drive belt adjustment.
      2. Drive belts are worn out.
   B. Corrective actions:
      1. Adjust tension to specified level.
      2. Replace drive belts.
6. Sudden increase in effluent solids.
   A. Causal factors:
      1. Hole in screen fabric.
      2. Screws that secure fabric are loose.
      3. Solids collection trough is overflowing.
   B. Corrective actions (where applicable):
      1. Repair fabric.
      2. Tighten screws.
      3. Reduce microscreen influent flow rate.
7. Decreased screen capacity after high-pressure washing.
   A. Causal factor:
      1. Iron or manganese oxide film on fabric.
   B. Corrective action:
      1. Clean screen with inhibited acid cleaner. Follow manufacturer's instruction.

18.12.3 Filtration

The purpose of filtration processes used in advanced treatment is to remove suspended solids. The specific operations associated with a filtration system are dependent on the equipment used. A general description of the process follows.

18.12.3.1 Filtration Process Description

Wastewater flows to a filter (gravity or pressurized). The filter contains single, dual, or multimedia. Wastewater flows through the media, which removes solids. The solids remain in the filter. Backwashing the filter as needed removes trapped solids. Backwash solids are returned to the plant for treatment. Processes typically remove 95 to 99% of the suspended matter.

18.12.3.2 Operation, Observation, and Troubleshooting Procedures

Operators routinely monitor filter operation to ensure optimum performance and to detect operational problems based on indication or observation of equipment malfunction or process suboptimal performance. We discuss operational problems typically encountered in the list that follows:

1. High effluent turbidity.
   A. Causal factors:
      1. Filter requires backwashing.
      2. Prior chemical treatment inadequate.
   B. Corrective actions (where applicable):
      1. Backwash unit as soon as possible.
      2. Adjust/control chemical dosage properly.
2. High head loss through the filter.
   A. Causal factor:
      1. Filter requires backwashing.
   B. Corrective action:
      1. Backwash unit as soon as possible.
3. High head loss through unit right after backwashing.
   A. Causal factors:
      1. Backwash cycle was insufficient.
      2. Surface scour or wash arm inoperative.
   B. Corrective actions (where applicable):
      1. Increase backwash time.
      2. Repair air scour or surface scrubbing arm.
4. Backwash water requirement exceeds 5%.
   A. Causal factors:
      1. Excessive solids in filter influent.
      2. Excessive filter aid dosage.
      3. Surface washing or air scour not operating.
      4. Surface washing or air scour not operated long enough during backwash cycle.
      5. Excessive backwash cycle used.
   B. Corrective actions (where applicable)
      1. Improve treatment prior to filtration.
      2. Reduce control or filter aid dose rates.
      3. Repair mechanical problem.
      4. Increase surface wash cycle time.
      5. Adjust backward cycle length.
5. Filter surface clogging.
   A. Causal factors:
      1. Inadequate prior treatment (single media filters).
      2. Excessive filter aid dosage (dual or mixed media filters).
      3. Inadequate surface wash cycle.
      4. Inadequate backwash cycle.
   B. Corrective actions (where applicable):
      1. Improve prior treatment.
      2. Replace single media with dual or mixed media.
      3. Reduce or eliminate filter aid.
      4. Provide adequate surface wash cycle.
      5. Provide adequate backwash cycle.
6. Short filter runs.
   A. Causal factor:
      1. High head loss.
   B. Corrective actions:

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1. Improve prior treatment.
2. Replace single media with dual or mixed media.
3. Reduce or eliminate filter aid.
4. Provide adequate surface wash cycle.
5. Provide adequate backwash cycle.

7. Filter effluent turbidity increases rapidly.
   A. Causal factors:
      1. Inadequate filter aid dosage.
      2. Filter aid system mechanical failure.
      3. Filter aid requirement has changed.
   B. Corrective actions (where applicable):
      1. Increase chemical dosage.
      2. Repair feed system.
      3. Adjust filter aid dose rate (do jar test).
8. Mud Ball Formation.
   A. Causal factors:
      1. Inadequate backwash flow rate.
      2. Inadequate surface wash.
   B. Corrective actions (where applicable):
      1. Increase backwash flow to specified levels.
      2. Increase surface wash cycle.
9. Gravel displacement.
   A. Causal factor:
      1. Air is entering the underdrains during backwash cycle.
   B. Corrective actions:
      1. Control backwash volume.
      2. Control backwash water head.
      3. Replace media (severe displacement).
10. Medium is lost during backwash cycle.
    A. Causal factors:
       1. Excessive backwash flows.
       2. Excessive auxiliary scour.
       3. Air attached to filter media, causing it to float.
    B. Corrective actions (where applicable):
       1. Reduce backwash flow rate.
       2. Stop auxiliary scour several minutes before end of backwash cycle.
       3. Increase backwash frequency to prevent bubble displacement and maintain maximum operating water depth above filter surface.
11. Filter backwash cycle not effective during warm weather.
    A. Causal factor:
       1. Decreased water viscosity due to higher temperatures.
    B. Corrective action:
       1. Increase backwash rate until required bed expansion is achieved.
12. Air binding causes premature head loss increase.
    A. Causal factors:
       1. Air bubble produced by exposing an influent containing high dissolved oxygen levels to less than atmospheric pressure.
       2. Pressure drops occurring during change-over to backwash cycle.
    B. Corrective actions (*where applicable*):
       1. Increase backwash frequency.
       2. Maintain maximum operating water depth.

18.12.4 Biological Nitrification

Biological nitrification is the first basic step of biological nitrification-denitrification.

In nitrification, the secondary effluent is introduced into another aeration tank, trickling filter, or biodisc. Because most of the carbonaceous BOD has already been removed, the microorganisms that drive in this advanced step are the nitrifying bacteria nitrosomonas and nitrobacter. In nitrification, the ammonia nitrogen is converted to nitrate nitrogen, producing a nitrified effluent. At this point, the nitrogen has not actually been removed, only converted to a form that is nontoxic to aquatic life and that does not cause an additional oxygen demand.

The nitrification process can be limited (performance affected) by alkalinity (requires 7.3 parts alkalinity to 1.0 part ammonia nitrogen), pH, DO availability, toxicity (ammonia or other toxic materials), and process MCRT (SRT). As a general rule, biological nitrification is more effective and achieves higher levels of removal during the warmer times of the year.

18.12.4.1 Operation, Observation, and Troubleshooting Procedures

Ensuring the nitrification process performs as per design requires the operator to monitor the process and make routine adjustments. The loss of solids from settling tank, RBC, or from a trickling filter are common problems that the operator must be able to identify as well as to take proper corrective actions. In these instances, the operator needs to be familiar with activated sludge system, RBC, or trickling filter operations.

The operator must also be familiar with other nitrification operational problems and must be able to take the proper corrective actions. We list typical nitrification operational problems and recommended corrective actions below:

1. pH decreases with loss of nitrification.
   A. Causal factors:
      1. Insufficient alkalinity available for process.
      2. Acid wastes in process influent.

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B. Corrective actions (where applicable):
   1. If process alkalinity is less than 30 mg/L, add lime or sodium hydroxide to process influent.
   2. Identify source and control of acid wastes.
2. Incomplete nitrification.
   A. Causal factors:
      1. Process is DO.
      2. Process is temperature limited.
      3. Influent nitorgen loading has increased.
      4. Low nitrifying bacteria population in process.
      5. Peak hourly ammonium concentrations exceed available oxygen supplies.
   B. Corrective actions (where applicable):
      1. Increase process aeration rate.
      2. Decrease process nitrogen loading.
      3. Increase nitrifying bacteria population.
      4. Put additional units in service.
      5. Modify operation to increase nitrogen removal.
      6. Decrease wasting or solids loss.
      7. Add settled raw sewage to nitrification unit to increase biological solids.
      8. Increase oxygen supply.
      9. Install flow equalization to minimize peaks.
3. SVI of nitrification sludge is very high (>250).
   A. Causal factor:
      1. Nitrification is occurring in the first stage (BOD removal sludge).
   B. Corrective actions (where applicable):
      1. Transfer sludge from first to second stages.
      2. Operate first stage at lower MCRT or SRT.

18.12.5 Biological Denitrifcation

Biological denitrification removes nitrogen from the wastewater. When bacteria come in contact with a nitrified element in the absence of oxygen, they reduce the nitrates to nitrogen gas, which escapes the wastewater. The denitrification process can be done in either an anoxic activated sludge system (suspended growth) or in a column system (fixed growth). The denitrification process can remove up to 85% or more of nitrogen.

After effective biological treatment, little oxygen demanding material is left in the wastewater when it reaches the denitrification process.

The denitrification reaction will only occur if an oxygen demand source exists when no DO is present in the wastewater. An oxygen demand source is usually added to reduce the nitrates quickly. The most common demand source added is soluble BOD or methanol. Approximately 3 mg/L of methanol is added for every 1 mg/L of nitrate-nitrogen.

Suspended growth denitrification reactors are mixed mechanically, but only enough to keep the biomass from settling without adding unwanted oxygen.

Submerged filters of different types of media may also be used to provide denitrification. A fine media downflow filter is sometimes used to provide both denitrification and effluent filtration. A fluidized sand bed where wastewater flows upward through a media of sand or activated carbon at a rate to fluidize the bed may also be used. Denitrification bacteria grow on the media.

18.12.5.1 Observation, Operation, and Troubleshooting Procedures

In operation of a denitrification process, operators monitor performance by observing various parameters. Parameters or other indicators and observations that demonstrate process malfunction or suboptimal performance indicate the need for various corrective actions. We discuss several of these indicators of poor process performance, their causal factors, and corrective actions in the sections that follow.

1. Process effluent: sudden increase in BOD.
   A. Causal factor:
      1. Excessive methanol or other organic matter present.
   B. Corrective actions (as required):
      1. Reduce methanol addition.
      2. Install automated methanol control system.
      3. Install aerated stabilization unit for removal of excess methanol.
2. Sudden increase in effluent nitrate concentration.
   A. Causal factors:
      1. Inadequate methanol control.
      2. Denitrification pH is outside 7.0 to 7.5 range required for process.
      3. Loss of solids from denitrification process due to pump failure.
      4. Excessive mixing introducing DO.
   B. Corrective actions (where applicable):
      1. Identify and correct control problem.
      2. Correct pH problem in nitrification process.
      3. Adjust pH at process influent.
      4. Correct denitrification sludge return.
      5. Increase denitrification sludge waste rate.
      6. Decrease denitrification sludge waste rate.
      7. Transfer sludge from carbonaceous units to denitrification unit.
      8. Reduce mixer speed.
      9. Remove some mixers from service.
3. High head loss (packed bed nitrification).
   A. Causal factors:
      1. Excessive solids in unit.
      2. Nitrogen gas accumulating in unit.

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B. Corrective action:
   1. Backwash unit 1 to 2 min and return to service.
4. Out of service packed bed unit binds on start-up.
   A. Causal factor:
      1. Solids have floated to top during shut down.
   B. Corrective action:
      1. Backwash units before removing from service and immediately before placing in service.

18.12.6 Carbon Adsorption

The main purpose of carbon adsorption used in advanced treatment processes is the removal of refractory organic compounds (non-BOD) and soluble organic material that are difficult to eliminate by biological or physical or chemical treatment.

In the carbon adsorption process, wastewater passes through a container filled either with carbon powder or carbon slurry. Organics adsorb onto the carbon (i.e., organic molecules are attracted to the activated carbon surface and are held there) with sufficient contact time.

A carbon system usually has several columns or basins used as contactors. Most contact chambers are either open concrete gravity-type systems or steel pressure containers applicable to either upflow or downflow operation.

With use, carbon loses its adsorptive capacity. The carbon must then be regenerated or replaced with fresh carbon. As head loss develops in carbon contactors, they are backwashed with clean effluent in much the same way the effluent filters are backwashed. Carbon used for adsorption may be in granular or powdered form.

Note: Powdered carbon is too fine for use in columns. It is usually added to the wastewater and later removed by coagulation and settling.

18.12.6.1 Operation, Observation, and Troubleshooting Procedures

In operation of a carbon adsorption system for advanced wastewater treatment, operators are primarily interested in monitoring the system to prevent excessive head loss, reduce levels of hydrogen sulfide in the carbon contactor, ensure that the carbon is not fouled, and ensure corrosion of metal parts and damage to concrete in contactors is minimal:

1. Excessive head loss.
   A. Casual factors:
      1. Highly turbid influent.
      2. Growth and accumulation of biological solids in unit.
      3. Excessive carbon fines due to deterioration during handling.
      4. Inlet or outlet screens plugged.
   B. Corrective actions (where applicable):
      1. Backwash unit vigorously.
      2. Correct problem in prior treatment steps.
      3. Operate as an expanded upflow bed to remove solids continuously.
      4. Increase frequency of backwashing for downflow beds.
      5. Improve soluble BOD removal in prior treatment steps.
      6. Remove carbon from unit and wash out fines.
      7. Replace carbon with harder carbon.
      8. Backflush screens.
2. Hydrogen sulfide is in carbon contactor.
   A. Causal factors:
      1. Low or no DO and nitrate in contactor influent.
      2. High influent BOD concentrations
      3. Excessive detention time in carbon contactor
   B. Corrective actions (where applicable):
      1. Add air, oxygen, or sodium nitrate to unit influent.
      2. Improve soluble BOD removal in prior treatment steps.
      3. Precipitate sulfides already formed with iron on chlorine.
      4. Reduce detention time by removing contactors from service.
      5. Backwash units more frequently and more violently, using air scour or surface wash.
3. Large decrease in COD removed or pounds of carbon regenerated.
   A. Causal factor:
      1. Carbon is fouled and losing efficiency.
   B. Corrective action:
      1. Improve regeneration process performance.
4. Corrosion of metal parts or damage to concrete in contactors.
   A. Causal factors:
      1. Hydrogen sulfide in carbon contactors.
      2. Holes in protective coatings exposed to dewatered carbon.
   B. Corrective actions:
      1. Add air, oxygen, or sodium nitrate to unit influent.
      2. Improve soluble BOD removal in prior treatment steps.
      3. Precipitate sulfides already formed with iron on chlorine.
      4. Reduce detention time by removing contactors from service.

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5. Backwash units more frequently and more violently, using air scour or surface wash.
6. Repair protective coatings.

18.12.7 Land Application

The application of secondary effluent onto a land surface can provide an effective alternative to the expensive and complicated advanced treatment methods discussed previously and the biological nutrient removal (BNR) system discussed briefly in Section 18.12.8. A high-quality polished effluent (i.e., effluent with high levels of TSS, BOD, phosphorus, and nitrogen compounds as well as refractory organics are reduced) can be obtained by the natural processes that occur as the effluent flows over the vegetated ground surface and percolates through the soil.

Limitations are involved with land application of wastewater effluent. For example, the process needs large land areas. Soil type and climate are also critical factors in controlling the design and feasibility of a land treatment process.

18.12.7.1 Types or Modes of Land Application

Three basic types or modes of land application or treatment are commonly used: irrigation (slow rate), overland flow, and infiltration-percolation (rapid rate). The basic objectives of these types of land applications and the conditions under which they can function vary.

In irrigation (also called slow rate), wastewater is sprayed or applied (usually by ridge-and-furrow surface spreading or by sprinkler systems) to the surface of the land. Wastewater enters the soil. Crops growing on the irrigation area utilize available nutrients. Soil organisms stabilize organic content of the flow. Water returns to the hydrologic (water) cycle through evaporation or by entering the surface water or groundwater (see Figure 18.12A).

The irrigation land application method provides the best results (compared with the other two types of land application systems) with respect to advanced treatment levels of pollutant removal. Not only are suspended solids and BOD significantly reduced by filtration of the wastewater, but also biological oxidation of the organics in the top few inches of soil occurs. Nitrogen is removed primarily by crop uptake, and phosphorus is removed by adsorption within the soil.

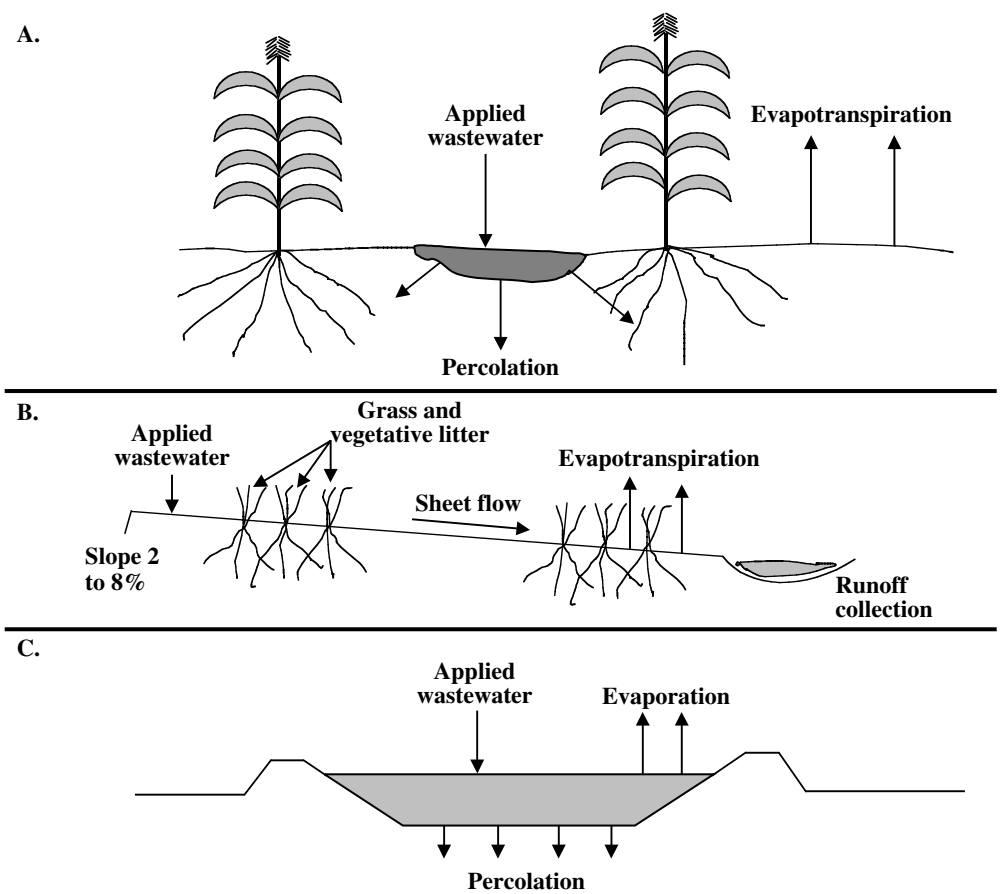

FIGURE 18.12 Land application. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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Irrigation expected performance levels are:

1. BOD — 98%
2. Suspended solids — 98%
3. Nitrogen — 85%
4. Phosphorus — 95%
5. Metals — 95%

The overland flow mode of land application used for water purification is accomplished by physical, chemical, and biological processes as the wastewater flows in a thin film down the relatively impermeable surface. In the process, wastewater sprayed over sloped terraces flows slowly over the surface. Soil and vegetation remove suspended solids, nutrients, and organics. A small portion of the wastewater evaporates. The remainder flows to collection channels. Collected effluent is discharged to surface waters (see Figure 18.2B).

Overflow flow expected performance levels are:

1. BOD — 92%
2. Suspended solids — 92%
3. Nitrogen — 70 to 90%
4. Phosphorus — 40 to 80%
5. Metals — 50%

In the infiltration-percolation (rapid rate) land application process, wastewater is sprayed/pumped to spreading basins (a.k.a. recharge basins or large ponds). Some wastewater evaporates. The remainder percolates/infiltrates into soil. Solids are removed by filtration. Water recharges the groundwater system. Most of the effluent percolates to the groundwater; very little of it is absorbed by vegetation (see Figure 18.2C). The filtering and adsorption action of the soil removes most of the BOD, TSS, and phosphorous from the effluent; however, nitrogen removal is relatively poor.

Infiltration-percolation expected performance levels are:

1. BOD — 85 to 99%
2. Suspended solids — 98%
3. Nitrogen — 0 to 50%
4. Phosphorus — 60 to 95%
5. Metals — 50 to 95%

18.12.7.1.1 Operation, Observation, and Troubleshooting Procedures

Performance levels are dependent on the land application process used. To be effective, operators must monitor the operation of the land application process employed. Experience has shown that these processes can be very effective, but problems exist when the flow contains potentially toxic materials that may become concentrated in the crops being grown on land. Along with this problem, other problems are common, including ponding, deterioration of distribution piping systems, malfunctioning sprinkler heads, waste runoff, irrigated crop die-off, poor crop growth, and too much flow rate:

1. In irrigated areas, water is ponding.
   A. Causal factors:
      1. Excessive application rate.
      2. Inadequate drainage because of groundwater levels.
      3. Damaged drainage wells.
      4. Inadequate well withdrawal rates.
      5. Damaged drain tiles.
      6. Broken pipe in distribution system.
   B. Corrective actions (where applicable):
      1. Reduce application rate to acceptable level.
      2. Irrigate in portions of site where groundwater is not a problem.
      3. Store wastewater until condition is corrected.
      4. Repair drainage wells.
      5. Increase drainage well pumping rates.
      6. Repair damaged drain tiles.
      7. Repair pipe.
2. Deterioration of distribution piping.
   A. Causal factors:
      1. Effluent remains in pipe for long periods.
      2. Different metals used in same line.
   B. Corrective actions (where applicable):
      1. Drain pipe after each use.
      2. Coat steel valves.
      3. Install cathodic or anodic protection.
3. No flow from source sprinkler nozzles.
   A. Casual factor:
      1. Nozzles clogged.
   B. Corrective action:
      1. Repair or replace screen on irrigation pump inlet.
4. Wastes are running off irrigation area.
   A. Causal factors:
      1. High sodium adsorption ratio has caused clay soil to become impermeable.
      2. Solids seal soil surface.
      3. Application rate is greater than soil infiltration rate.
      4. Break in distribution piping.
      5. Soil permeability has decreased because of continuous application of wastewater.
      6. Rain has saturated the soil.
   B. Corrective actions (where applicable):
      1. Feed calcium and magnesium to maintain a sodium adsorption ratio of less than 9.
      2. Strip crop area.

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3. Reduce application rate to acceptable level.
4. Repair system.
5. Allow 2- to 3-d rest period between each application.
6. Store wastewater until soil has drained.

5. Irrigated crop is dead.
   A. Causal factors:
      1. Too much or not enough water has been applied.
      2. Wastewater contains toxic materials in toxic concentrations.
      3. Excessive insecticide or herbicide applied.
      4. Inadequate drainage has flooded root zone of crop.
   B. Corrective actions (where applicable):
      1. Adjust application rate to appropriate level.
      2. Eliminate source of toxicity.
      3. Apply only as permitted or directed.
6. Poor crop growth.
   A. Causal factors:
      1. Too little nitrogen or phosphorus.
      2. Timing of nutrient applications does not coincide with plant nutrient need.
   B. Corrective actions (where applicable):
      1. Increase application rate to supply nitrogen and phosphorus.
      2. Augment nitrogen and phosphorus of wastewater with commercial fertilizer applications.
      3. Adjust application schedule to match crop need.
7. Irrigation pump has normal pressure, but above average flow rate.
   A. Causal factors:
      1. Broken main, riser, or lateral.
      2. Leaking gasket.
      3. Sprinkler head or nozzle is missing.
      4. Too many distribution laterals are in service at one time.
   B. Corrective actions (where applicable):
      1. Locate and repair problems.
      2. Locate and replace defective gasket.
      3. Correct valving to adjust number of laterals in service.
8. Irrigation pump has above average pressure, but below average flow.
   A. Causal factor:
      1. Blockage in system.
   B. Corrective action:
      1. Locate and correct blockage.
9. Irrigation pump has below average pressure and flow rate
   A. Causal factors:
      1. Worn impeller.
      2. Partially clogged pump inlet screen.
   B. Corrective actions (where applicable):
      1. Replace impeller.
      2. Clean screen.
10. Excessive erosion occurring.
    A. Causal factors:
       1. Excessive application rates.
       2. Inadequate crop coverage.
    B. Coverage actions (where applicable):
       1. Reduce application rate.
11. Odor complaints.
    A. Causal factors:
       1. Wastes are turning septic during transport to treatment or irrigation site.
       2. Storage reservoirs are septic.
    B. Corrective actions (where applicable):
       1. Aerate or chemically treat wastes during transport.
       2. Install cover over discharge point. Collect and treat gases before release.
       3. Improve pretreatment.
       4. Aerate storage reservoirs.
12. Center pivot irrigation rigs stuck in mud.
    A. Causal factors:
       1. Excessive application rates.
       2. Improper rig or tires.
       3. Poor drainage.
    B. Corrective actions:
       1. Reduce application rate.
       2. Install tire with higher flotation capabilities.
13. Nitrate in groundwater near irrigation site is increasing.
    A. Causal factors:
       1. Nitrogen application rate does not balance with crop need.
       2. Applications are occurring during dormant periods.
       3. Crop is not being properly harvested and removed.
    B. Corrective actions (where applicable):
       1. Change to crop with higher nitrogen requirement.
       2. Adjust schedule to apply only during active growth periods.
       3. Harvest and remove crop as required.

18.12.8 Biological Nutrient Removal

Recent experience has shown that BNR systems are reliable and effective in removing nitrogen and phosphorus. The process is based upon the principle that under specific

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conditions, microorganisms will remove more phosphorus and nitrogen than is required for biological activity. Several patented processes are available for this purpose. Performance depends on the biological activity and the process employed.

18.13 SOLIDS (SLUDGE OR BIOSOLIDS) HANDLING

The wastewater treatment unit processes described to this point remove solids and BOD from the wastestream before the liquid effluent is discharged to its receiving waters. What remains to be disposed of is a mixture of solids and wastes, called process residuals; they are more commonly referred to as sludge or biosolids.

Note: Sludge is the commonly accepted name for wastewater solids. If wastewater sludge is used for beneficial reuse (e.g., as a soil amendment or fertilizer), it is commonly called biosolids.

The most costly and complex aspect of wastewater treatment can be the collection, processing, and disposal of sludge. This is the case because the quantity of sludge produced may be as high as 2% of the original volume of wastewater, depending somewhat on the treatment process being used.

Because sludge can be as much as 97% water content and the cost of disposal will be related to the volume of sludge being processed, one of the primary purposes or goals (along with stabilizing it so it is no longer objectionable or environmentally damaging) of sludge treatment is to separate as much of the water from the solids as possible. Sludge treatment methods may be designed to accomplish both of these purposes.

Sludge treatment methods are generally divided into three major categories: thickening, stabilization, and dewatering. Many of these processes include complex sludge treatment methods (i.e., heat treatment, vacuum filtration, incineration and others).

18.13.1 Sludge: Background Information

When we speak of sludge or biosolids, we are speaking of the same substance or material; each is defined as the suspended solids removed from wastewater during sedimentation and concentrated for further treatment and disposal or reuse. The difference between the terms sludge and biosolids is determined by the way they are managed. (Note: The task of disposing, treating or reusing wastewater solids is called sludge or biosolids management.) Sludge is typically seen as wastewater solids that are disposed. Biosolids is the same substance managed for reuse, commonly called beneficial reuse (e.g., for land application as a soil amendment, such as biosolids compost).

Note that even as wastewater treatment standards have become more stringent because of increasing environmental regulations, the volume of wastewater sludge has also increased.

Note also that before sludge can be disposed of or reused, it requires some form of treatment to reduce its volume, stabilize it, and inactivate pathogenic organisms.

Sludge forms initially as a 3 to 7% suspension of solids; with each person typically generating about 4 gal of sludge per week, the total quantity generated each day, week, month, and year is significant. Because of the volume and nature of the material, sludge management is a major factor in the design and operation of all water pollution control plants.

Note: Wastewater solids account for more than half of the total costs in a typical secondary treatment plant.

18.13.1.1 Sources of Sludge

Wastewater sludge is generated in primary, secondary, and chemical treatment processes. In primary treatment, the solids that float or settle are removed. The floatable material makes up a portion of the solid waste known as scum. Scum is not normally considered sludge; however, it should be disposed of in an environmentally sound way. The settleable material that collects on the bottom of the clarifier is known as primary sludge. Primary sludge can also be referred to as raw sludge because it has not undergone decomposition. Raw primary sludge from a typical domestic facility is quite objectionable and has a high percentage of water — two characteristics that make handling difficult.

Those solids not removed in the primary clarifier are carried out of the primary unit. These solids are known as colloidal suspended solids. The secondary treatment system (i.e., trickling filter, activated sludge, etc.) is designed to change those colloidal solids into settleable solids that can be removed. Once in the settleable form, these solids are removed in the secondary clarifier. The sludge at the bottom of the secondary clarifier is called secondary sludge. Secondary sludges are light and fluffy and more difficult to process than primary sludges. In short, secondary sludges do not dewater well.

The addition of chemicals and various organic and inorganic substances prior to sedimentation and clarification may increase the solids capture and reduce the amount of solids lost in the effluent. This chemical addition results in the formation of heavier solids that trap the colloidal solids or convert dissolved solids to settleable solids. The resultant solids are known as chemical sludges. As chemical usage increases, so does the quantity of sludge that must be handled and disposed. Chemical sludges can be very difficult to process; they do not dewater well and contain lower percentages of solids.

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TABLE 18.8
Typical Water Content of Sludges

Water Treatment Process	% Moisture of Sludge Generated	Water/lb Sludge Solids
Primary Sedimentation	95	19
Trickling Filter		
Humus (low rate)	93	13.3
Humus (high rate)	97	32.3
Activated sludge	99	99

Source: U.S. Environmental Protection Agency, Operational Manual: Sludge Handling and Conditioning, EPA-430/9–78–002, 1978.

TABLE 18.9
Distribution of Water in an Activated Sludge

Water Type	% Volume
Free Water	75
Floc Water	20
Capillary Water	2
Particle Water	2.5
Solids	0.5
Total	100

Source: U.S. Environmental Protection Agency, Operational Manual: Sludge Handling and Conditioning, EPA-430/9–78–002, 1978.

18.13.1.2 Sludge Characteristics

The composition and characteristics of sewage sludge vary widely and can change considerably with time. Notwithstanding these facts, the basic components of wastewater sludge remain the same. The only variations occur in quantity of the various components as the type of sludge and the process from which it originated changes.

The main component of all sludges is water. Prior to treatment, most sludges contain 95 to +99% water (see Table 18.8). This high water content makes sludge handling and processing extremely costly in terms of both money and time. Sludge handling may represent up to 40% of the capital cost and 50% of the operation cost of a treatment plant. As a result, the importance of optimum design for handling and disposal of sludge cannot be overemphasized. The water content of the sludge is present in a number of different forms. Some forms can be removed by several sludge treatment processes, allowing the same flexibility in choosing the optimum sludge treatment and disposal method.

The various forms of water and their approximate percentages for a typical activated sludge are shown in Table 18.9. The forms of water associated with sludges are:

Free water water that is not attached to sludge solids in any way. This can be removed by simple gravitational settling.

Floc water water that is trapped within the floc and travels with them. Its removal is possible by mechanical dewatering.

Capillary water water that adheres to the individual particles and can be squeezed out of shape and compacted.

Particle water water that is chemically bound to the individual particles and can't be removed without inclination.

From a public health view, the second and probably more important component of sludge is the solids matter. Representing from 1 to 8% of the total mixture, these solids are extremely unstable. Wastewater solids can be classified into two categories based on their origin: organic and inorganic. Organic solids in wastewater, are materials that are or were at one time alive and that will burn or volatilize at 550°C after 15 minutes in a muffle furnace. The percent of organic material within a sludge will determine how unstable it is.

The inorganic material within a sludge will determine how stable it is. The inorganic solids are those solids that were never alive and will not burn or volatilize at 550°C after 15 minutes in a muffle furnace. Inorganic solids are generally not subject to breakdown by biological action and are considered stable. Certain inorganic solids, however, can create problems when related to the environment (e.g., heavy metals such as copper, lead, zinc, mercury, and others). These can be extremely harmful if discharged.

Organic solids may be subject to biological decomposition in either an aerobic or anaerobic environment. Decomposition of organic matter (with its production of objectionable by-products) and the possibility of toxic organic solids within the sludge compound the problems of sludge disposal.

Note: Before moving on to a discussion of the fundamentals of sludge treatment methods, it is important to begin by covering sludge pumping calculations. It is important to point out that it is difficult (if not impossible) to treat the sludge unless it is pumped to the specific sludge treatment process.

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18.13.1.3 Sludge Pumping Calculations

While on shift, wastewater operators are often called upon to make various process control calculations. An important calculation involves sludge pumping. The sludge pumping calculations the operator may be required to make during plant operations (and should be known for licensure examinations) are covered in this section.

18.13.1.3.1 Estimating Daily Sludge Production

The calculation for estimation of the required sludge-pumping rate provides a method to establish an initial pumping rate or to evaluate the adequacy of the current withdrawal rate:

$$\text{Est. Pump Rate} = \text{gpm} \qquad (18.55)$$

$$\frac{(\text{Influent TSS Conc.} - \text{Effluent TSS Conc.}) \times \text{Flow} \times 8.34}{\%\ \text{Solids in Sludge} \times 8.34\ \text{lb/gal} \times 1440\ \text{min/d}}$$

EXAMPLE 18.59

Problem:

The sludge withdrawn from the primary settling tank contains 1.4% of solids. The unit influent contains 285 mg/L TSS and the effluent contains 140 mg/L TSS. If the influent flow rate is 5.55 MGD, what is the estimated sludge withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Sludge Rate, gpm} = \frac{(285\ \text{mg/L} - 140\ \text{mg/L}) \times 5.55 \times 8.34}{0.014 \times 8.34\ \text{lb/gal} \times 1440\ \text{min/d}}$$

$$= 40\ \text{gpm}$$

The following chart is used for Examples 18.60 to 18.65.

Operating time	15 min/c
Frequency	24 c/d
Pump rate	120 gal/min
Solids	3.7%
Volatile matter	66%

18.13.1.3.2 Sludge Pumping Time

The sludge pumping time is the total time the pump operates during a 24-h period in minutes:

$$\text{Pump Operating Time} = \text{Time/c (min)} \times \text{Frequency (c/d)} \qquad (18.56)$$

EXAMPLE 18.60

Problem:

What is the pump operating time?

Solution:

$$\text{Pump Operating Time} = 15\ \text{min/h} \times 24\ \text{c/d}$$

$$= 360\ \text{min/d}$$

18.13.1.3.3 Sludge Pumped in Gallons per day

Use Equation 18.57 to calculate the amount of sludge pumped in gallons per day:

$$\text{Sludge Pumped (gal/d)} = \text{Operating Time (min/d)} \times \text{Pump Rate (gal/min)} \qquad (18.57)$$

EXAMPLE 18.61

Problem:

What is the amount of sludge pumped in gallons per day?

Solution:

$$\text{Sludge Pumped (gal/d)} = 360\ \text{min/d} \times 120\ \text{gal/min}$$

$$= 43{,}200\ \text{gal/d}$$

18.13.1.3.4 Sludge Pumped in Pounds per Day

Use Equation 18.58 to calculate the amount of sludge pumped in pounds per day:

$$\text{Sludge Pumped (lb/d)} = \text{Sludge Pumped (gal/d)} \times 8.34\ \text{lb/gal} \qquad (18.58)$$

EXAMPLE 18.62

Problem:

What is the amount of sludge pumped in pounds per day?

Solution:

$$\text{Sludge Pumped (lb/d)} = 43{,}200\ \text{gal/d} \times 8.34\ \text{lb/gal}$$

$$= 360{,}300\ \text{lb/d}$$

18.13.1.3.5 Solids Pumped in Pounds per Day

Use Equation 18.59 to calculate the amount of sludge pumped in pounds per day:

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$$\text{Solids Pumped (lb/d)} = \text{Sludge Pumped (lb/d)} \times \text{\% Solids} \quad (18.59)$$

Example 18.63

Problem:

What is the amount of solid pumped in pounds per day?

Solution:

$$\text{Solids Pumped (lb/d)} = 360{,}300 \text{ lb/d} \times 0.0370$$
$$= 13{,}331 \text{ lb/d}$$

18.13.1.3.6 Volatile Matter Pumped in Pounds per Day

Use Equation 18.60 to calculate the amount of volatile matter pumped in pounds per day:

$$\text{VM (lb/d)} = \text{Solids Pumped (lb/d)} \times \text{\%VM} \quad (18.60)$$

Example 18.64

Problem:

What is the amount of volatile matter pumped in pounds per day?

Solution:

$$\text{VM (lb/d)} = 13{,}331 \text{ lb/d} \times 0.66$$
$$= 8.798 \text{ lb/d}$$

If you wish to calculate the pounds of solids or the pounds of volatile solids removed per day, the individual equations demonstrated above can be combined into a single calculation:

$$\begin{aligned}\text{Solids (lb/d)} &= \text{Pump Time (min/c)} \times \text{Frequency (c/d)} \times \\ &\quad \text{Rate (gal/min)} \times 8.34 \text{ lb/gal} \times \\ &\quad \text{\%Solids VM (lb/d)} \qquad (18.61) \\ &= \text{time (min/c)} \times \text{Frequency (c/d)} \times \\ &\quad \text{Rate (gal/min)} \times 8.34 \times \\ &\quad \text{\%Solids} \times \text{\%VM}\end{aligned}$$

Example 18.65

Problem:

Use Equation 18.61 to calculate the amount of (1) solids and (2) volatile matter removed in pounds per day.

Solution:

1. Amount of solids removed in pounds per day:

$$\text{Solids (lb/d)} = 15 \text{ min/c} \times 24 \text{ c/d} \times 120 \text{ gal/min} \times 8.34 \times 0.0370$$
$$= 13{,}331 \text{ lb/d}$$

2. Amount of volatile solids in pounds per day:

$$\text{VM (lb/d)} = 15 \text{ min/c} \times 24 \text{ c/d} \times 120 \text{ gal/min} \times 8.34 \times 0.0370 \times 0.66$$
$$= 8798 \text{ lb/d}$$

18.13.1.3.7 Sludge Production in Pounds per Million Gallons

A common method of expressing sludge production is in pounds of sludge per million gallons of wastewater treated:

$$\text{Sludge (lb/MG)} = \frac{\text{Total Sludge Production (lb)}}{\text{Total Wastewater Flow (MG)}} \quad (18.62)$$

Example 18.66

Problem:

Records show that the plant has produced 85,000 gal of sludge during the past 30 d. The average daily flow for this period was 1.2 MGD. What was the plant's sludge production in pounds per million gallons?

Solution:

$$\text{Sludge (lb/MG)} = \frac{85{,}000 \text{ gal} \times 8.34 \text{ lb/gal}}{1.2 \text{ MGD} \times 30 \text{ d}}$$
$$= 19{,}692 \text{ lb/MG}$$

18.13.1.3.8 Sludge Production in Wet Tons per Year

Sludge production can also be expressed in terms of the amount of sludge (water and solids) produced per year. This is normally expressed in wet tons per year:

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$$\text{Sludge}\left(\text{wet tons/year}\right) = \frac{\text{Sludge Production}\left(\text{lb/MG}\right) \times \text{Average Daily Flow}\left(\text{MGD}\right) \times 365\ \text{d/year}}{2000\ \text{lb/ton}} \tag{18.63}$$

EXAMPLE 18.67

Problem:

The plant is currently producing sludge at the rate of 16,500 lb/MG. The current average daily wastewater flow rate is 1.5 MGD. What will be the total amount of sludge produced per year in wet tons per year?

Solution:

$$\text{Sludge}\left(\text{wet tons/year}\right) = \frac{16{,}500\ \text{lb/MG} \times 1.5\ \text{MGD} \times 365\ \text{d/year}}{2000\ \text{lb/ton}} = 4517\ \text{wet tons/year}$$

18.13.1.4 Sludge Treatment: An Overview

The release of wastewater solids without proper treatment could result in severe damage to the environment. We must have a system to treat the volume of material removed as sludge throughout the system. Release without treatment would defeat the purpose of environmental protection. A design engineer can choose from many processes when developing sludge treatment systems. No matter what the system or combination of systems chosen, the ultimate purpose will be the same: the conversion of wastewater sludges into a form that can be handled economically and disposed of without damaging the environment or creating nuisance conditions. Leaving either condition unmet will require further treatment. The degree of treatment will generally depend on the proposed method of disposal.

Sludge treatment processes can be classified into a number of major categories. In this handbook, we discuss the processes shown in Figure 18.13: thickening, digestion (or stabilization), de-watering, incineration, and land application. Each of these categories has then been further subdivided according to the specific processes that are used to accomplish sludge treatment.

As mentioned, the importance of adequate, efficient sludge treatment cannot be overlooked when designing wastewater treatment facilities. The inadequacies of a sludge treatment system can severely affect a plant's overall performance capabilities. The inability to remove and process solids as fast as they accumulate in the process can lead to the discharge of large quantities of solids to receiving waters.

Even with proper design and capabilities in place, no system can be effective unless it is properly operated. Proper operation requires proper operator performance. Proper operator performance begins and ends with proper training.

18.13.2 SLUDGE THICKENING

The solids content of primary, activated, trickling-filter, or even mixed sludge (i.e., primary plus activated sludge) varies considerably, depending on the characteristics of the sludge. Note that the sludge removal and pumping facilities and the method of operation also affect the solids

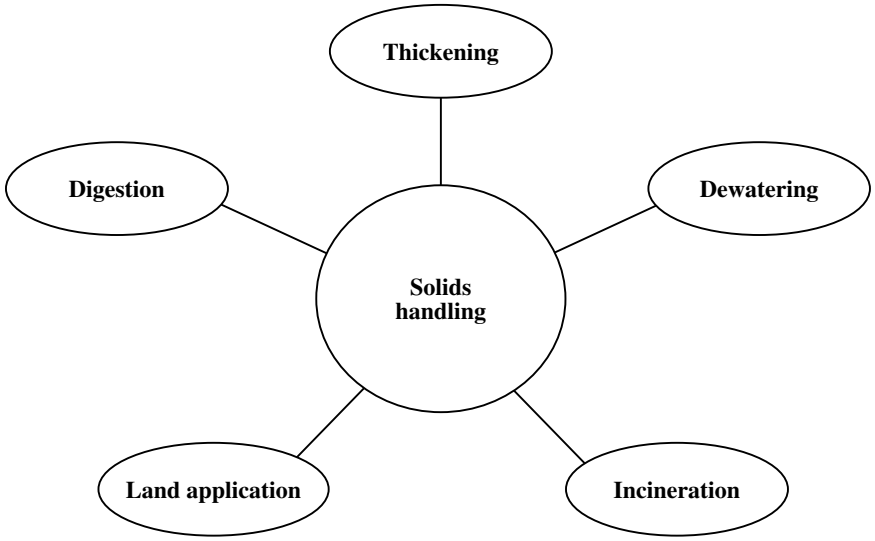

FIGURE 18.13 Major solids handling processes. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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content. Sludge thickening (or concentration) is a unit process used to increase the solids content of the sludge by removing a portion of the liquid fraction. By increasing the solids content, more economical treatment of the sludge can be effected. Sludge thickening processes include:

1. Gravity thickeners
2. Flotation thickeners
3. Solids concentrators

18.13.2.1 Gravity Thickening

Gravity thickening is most effective on primary sludge. In operation, solids are withdrawn from primary treatment (and sometimes secondary treatment) and pumped to the thickener. The solids buildup in the thickener forms a solids blanket on the bottom. The weight of the blanket compresses the solids on the bottom and "squeezes" the water out. By adjusting the blanket thickness, the percent of solids in the underflow (solids withdrawn from the bottom of the thickener) can be increased or decreased. The supernatant (clear water) that rises to the surface is returned to the wastewater flow for treatment.

Daily operations of the thickening process include pumping, observation, sampling and testing, process control calculations, maintenance and housekeeping.

Note: The equipment employed in thickening depends on the specific thickening processes used.

Equipment used for gravity thickening consists of a thickening tank, which is similar in design to the settling tank used in primary treatment. Generally the tank is circular and provides equipment for continuous solids collection. The collector mechanism uses heavier construction than a settling tank's because the solids being moved are more concentrated. The gravity thickener pumping facilities (i.e., pump and flow measurement) are used for withdrawal of thickened solids.

Performance of gravity thickeners (i.e., the solids concentrations achieved) typically results in producing 8 to 10% solids from primary underflow, 2 to 4% solids from waste activated sludge, 7 to 9% solids from trickling filter residuals, and 4 to 9% from combined primary and secondary residuals.

The performance of gravity thickening processes depends on various factors, including:

1. Type of sludge
2. Condition of influent sludge
3. Temperature
4. Blanket depth
5. Solids loading
6. Hydraulic loading
7. Solids retention time
8. HDT

18.13.2.2 Flotation Thickening

Flotation thickening is used most efficiently for waste sludges from suspended-growth biological treatment process, such as the activated sludge process. In operation, recycled water from the flotation thickener is aerated under pressure. During this time the water absorbs more air than it would under normal pressure. The recycled flow together with chemical additives (if used) is mixed with the flow. When the mixture enters the flotation thickener, the excess air is released in the form of fine bubbles. These bubbles become attached to the solids and lift them toward the surface. The accumulation of solids on the surface is called the float cake. As more solids are added to the bottom of the float cake, it becomes thicker and water drains from the upper levels of the cake. The solids are then moved up an inclined plane by a scraper and discharged. The supernatant leaves the tank below the surface of the float solids and is recycled or returned to the wastestream for treatment. Flotation thickener performance is typically 3 to 5% solids for WAS with polymer addition and 2 to 4% solids without polymer addition.

The flotation thickening process requires pressurized air, a vessel for mixing the air with all or part of the process residual flow, a tank for the flotation process to occur, solids collector mechanisms to remove the float cake (solids) from the top of the tank, and accumulated heavy solids from the bottom of the tank. Since the process normally requires chemicals be added to improve separation, chemical mixing equipment, storage tanks, and metering equipment to dispense the chemicals at the desired dose are required.

The performance of dissolved air-thickening process depends on various factors that include:

1. Bubble size
2. Solids loading
3. Sludge characteristics
4. Chemical selection
5. Chemical dose

18.13.2.3 Solids Concentrators

Solids concentrators (belt thickeners) usually consist of a mixing tank, chemical storage and metering equipment, and a moving porous belt. In operation, the process residual flow is chemically treated and then spread evenly over the surface of the moving porous belt. As the flow is carried down the belt (similar to a conveyor belt) the solids are mechanically turned or agitated and water drains through the belt. This process is primarily used in facilities where space is limited.

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18.13.2.3.1 Operation, Observation, and Troubleshooting Procedures

As with other unit treatment processes, proper operation of sludge thickeners depends on operator observation. The operator must make routine adjustment of sludge addition and withdrawal rates to achieve desired blanket thickness. Sampling and analysis of influent sludge, supernatant, and thickened sludge are also required. If possible, sludge addition and withdrawal should be continuous to achieve optimum performance. Mechanical maintenance is also required.

Expected performance ranges for gravity and dissolved air flotation thickeners are listed below:

1. Primary sludge — 8 to 19% solids
2. WAS — 2 to 4% solids
3. Trickling filter sludge — 7 to 9% solids
4. Combined sludges — 4 to 9% solids

Typical operational problems with sludge thickeners include odors, rising sludge, thickened sludge below desired solids concentration, a dissolved air concentration that is too low, an effluent flow containing excessive solids, and torque alarm conditions.

Gravity Thickener

1. Odors and rising sludge.
   A. Causal factors:
      1. Sludge withdrawal rate is too low.
      2. Overflow rate is too low.
      3. Septicity in the thickener.
   B. Corrective actions (where applicable):
      1. Increase sludge withdrawal rate.
      2. Increase influent flow rate.
      3. Add chlorine, permanganate, or peroxide to influent.
2. Thickened sludge is below desired solids concentration.
   A. Causal factors:
      1. Overflow rate is too high.
      2. Sludge withdrawal rate is too high.
      3. Short-circuiting.
   B. Corrective actions (where applicable):
      1. Decrease influent sludge flow rate.
      2. Decrease pump rate for sludge withdrawal.
      3. Identify cause and correct.
3. Torque alarm is activated.
   A. Causal factors:
      1. Heavy sludge accumulation.
      2. Collector mechanism is jammed.
   B. Corrective actions (where applicable):
      1. Agitate sludge blanket to decrease density.
      2. Increase sludge withdrawal rate.
      3. Attempt to locate and remove obstacle.
      4. Dewater tank and remove obstacle.

Dissolved Air Flotation Thickener

1. Float solids concentration is too low.
   A. Causal factors:
      1. Skimmer speed is too high.
      2. Unit is overloaded.
      3. Insufficient polymer dose.
      4. Excessive air-to-solids ratio.
      5. Low dissolved air levels.
   B. Corrective actions (where applicable):
      1. Adjust skimmer speed to permit concentration to occur.
      2. Stop sludge flow through unit or purge with recycles flow.
      3. Determine proper chemical dose and adjust.
      4. Reduce airflow to pressurization tank.
      5. Identify malfunction and correct.
2. Dissolved air concentration is too low.
   A. Causal factor:
      1. Mechanical malfunction.
   B. Corrective action:
      1. Identify cause and correct.
3. Effluent (subnatant) flow contains excessive solids.
   A. Causal factors:
      1. Unit is overloaded.
      2. Chemical dose is too low.
      3. Skimmer is not operating.
      4. Low air-to-solids ratio.
      5. Solids buildup in thickener.
   B. Corrective actions (where applicable):
      1. Turn off sludge flow.
      2. Purge unit with recycle.
      3. Determine proper chemical dose and blow.
      4. Turn skimmer on.
      5. Adjust skimmer speed.
      6. Increase airflow to pressurization system.
      7. Remove sludge from tank.

18.13.2.3.2 Process Calculations (Gravity and Dissolved Air Flotation)

Sludge thickening calculations are based on the concept that the solids in the primary or secondary sludge are equal to the solids in the thickened sludge. Assuming a negligible amount of solids are lost in the thickener overflow, the solids are the same. Note that the water is removed to thicken the sludge and results in higher percent solids.

18.13.2.3.2.1 Estimating Daily Sludge Production

Equation 18.76 provides a method to establish an initial pumping rate or to evaluate the adequacy of the current pump rate:

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$$\text{Surf. Loading, gal/d/ft}^2 = \frac{\text{Sludge Applied to the Thickener, gpd}}{\text{Thickener Area, ft}^2} \quad (18.64)$$

EXAMPLE 18.68

Problem:

The sludge withdrawn from the primary settling tank contains 1.5% of solids. The unit influent contains 280 mg/L TSS, and the effluent contains 141 mg/L. If the influent flow rate is 5.55 MGD, what is the estimated sludge withdrawal rate in gallons per minute (assuming the pump operates continuously)?

Solution:

$$\text{Surface Loading} = \frac{32{,}000 \text{ gpd}}{0.785 \times 70 \text{ ft} \times 70 \text{ ft}}$$

$$= 8.32 \text{ gpd/ft}^2$$

18.13.2.3.2.2 Surface Loading Rate

Surface loading rate (surface settling rate) is hydraulic loading — the amount of sludge applied per square foot of gravity thickener:

$$\text{Surface Loading Rate } \left(\text{gal/d/ft}^2\right) = \frac{\text{Sludge Applied to the Thickener (gal/d)}}{\text{Thickener Area } \left(\text{ft}^2\right)} \quad (18.65)$$

EXAMPLE 18.69

Problem:

The 70-ft diameter gravity thickener receives 32,000 gal/d of sludge. What is the surface loading in gallons per square foot per day?

Solution:

$$\text{Surface Loading Rate } \left(\text{gal/d/ft}^2\right)$$

$$= \frac{32{,}000 \text{ gal/d}}{0.785 \times 70 \text{ ft} \times 70 \text{ ft}}$$

$$= 8.32 \text{ gal/d/ft}^2$$

18.13.2.3.2.3 Solids Loading Rate

The solids loading rate is the pounds of solids per day being applied to 1 ft^2 of tank surface area. The calculation uses the surface area of the bottom of the tank. It assumes the floor of the tank is flat and has the same dimensions as the surface.

$$\text{Solids Loading Rate } \left(\text{lb/d/ft}^2\right) = \frac{\text{\%Sludge Solids} \times \text{Sludge Flow (gal/d)} \times 8.34 \text{ lb/gal}}{\text{Thickener Area } \left(\text{ft}^2\right)} \quad (18.66)$$

EXAMPLE 18.70

Problem:

The thickener influent contains 1.6% of solids. The influent flow rate is 39,000 gal/d. The thickener is 50 ft in diameter and 10 ft deep. What is the solid loading in pounds per day?

Solution:

$$\text{Solids Loading Rate } \left(\text{lb/d/ft}^2\right)$$

$$= \frac{0.016 \times 39{,}000 \text{ gal/d} \times 8.34 \text{ lb/gal}}{0.785 \times 50 \text{ ft} \times 50 \text{ ft}}$$

$$= 2.7 \text{ lb/d/ft}^2$$

18.13.2.3.2.4 Concentration Factor

The concentration factor (CF) represents the increase in concentration resulting from the thickener:

$$\text{CF} = \frac{\text{Thickened Sludge Concentration (\%)}}{\text{Influent Sludge Concentration (\%)}} \quad (18.67)$$

EXAMPLE 18.71

Problem:

The influent sludge contains 3.5% solids. The thickened sludge solids concentration is 7.7%. What is the concentration factor?

Solution:

$$\text{CF} = \frac{7.7\%}{3.5\%} = 2.2$$

18.13.2.3.2.5 Air-to-Solids Ratio

The air-to-solids ratio is the ratio between the pounds of solids entering the thickener and the pounds of air being applied:

$$\text{Air:Solids Ratio} = \frac{\text{Air Flow } \left(\text{ft}^3\text{/min}\right) \times 0.075 \left(\text{lb/ft}^3\right)}{\text{Sludge Flow (gal/min)} \times \text{\%Solids} \times 8.34 \text{ lb/gal}} \quad (18.68)$$

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EXAMPLE 18.72

Problem:

The sludge pumped to the thickener is 0.85% solids. The airflow is 13 ft^3/min. What is the air-to-solids ratio if the current sludge flow rate entering the unit is 50 gal/min?

Solution:

$$\text{Air:Solids Ratio} = \frac{13\ \text{ft}^3/\text{min} \times 0.075\ \text{lb/ft}^3}{50\ \text{gal/min} \times 0.0085 \times 8.34\ \text{lb/gal}} = 0.28$$

18.13.2.3.2.6 Recycle Flow in Percent

The amount of recycle flow expressed as a percent:

$$\text{Recycle Flow}\ (\%) = \frac{\text{Recycle Flow Rate}\ (\text{gal/min}) \times 100}{\text{Sludge Flow}\ (\text{gal/min})} \quad (18.69)$$

EXAMPLE 18.73

Problem:

The sludge flow to the thickener is 80 gal/min. The recycle flow rate is 140 gal/min. What is the recycle flow?

Solution:

$$\text{Recycle Flow}\ (\%) = \frac{140\ \text{gal/min} \times 100}{80\ \text{gal/min}} = 175\%$$

18.13.3 SLUDGE STABILIZATION

The purpose of sludge stabilization is to reduce volume, stabilize the organic matter, and eliminate pathogenic organisms to permit reuse or disposal. The equipment required for stabilization depends on the specific process used. Sludge stabilization processes include:

1. Aerobic digestion
2. Anaerobic digestion
3. Composting
4. Lime stabilization
5. Wet air oxidation (heat treatment)
6. Chemical oxidation (chlorine oxidation)
7. Incineration

18.13.3.1 Aerobic Digestion

Equipment used for aerobic digestion consists of an aeration tank (digester) which is similar in design to the aeration tank used for the activated sludge process. Either diffused or mechanical aeration equipment is necessary to maintain the aerobic conditions in the tank. Solids and supernatant removal equipment is also required.

TABLE 18.10
Aerobic Digester Normal Operating Levels

Parameter	Normal Levels
Detention time (d)	10–20
Volatile solids loading $lb/ft^3/d$	0.1–0.3
DO (mg/L)	1.0
pH	5.9–7.7
Volatile Solids Reduction	40–50%

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

In operation, process residuals (sludge) are added to the digester and aerated to maintain a DO concentration of 1.0 mg/L. Aeration also ensures that the tank contents are well mixed. Generally, aeration continues for approximately 20 d retention time. Aeration is periodically stopped and the solids are allowed to settle. Sludge and the clear liquid supernatant are withdrawn as needed to provide more room in the digester. When no additional volume is available, mixing is stopped for 12 to 24 h before solids are withdrawn for disposal. Process control testing should include alkalinity, pH, percent solids, percent volatile solids for influent sludge, supernatant, digested sludge, and digester contents.

Normal operating levels for an aerobic digester are listed in Table 18.10.

A typical operational problem associated with an aerobic digester is pH control. For example, when pH drops, this may indicate normal biological activity or low influent alkalinity. This problem is corrected by adding alkalinity (lime, bicarbonate, etc.).

18.13.3.1.1 Process Control Calculations: Aerobic Digester

Wastewater operators (who operate aerobic digesters) are required to make certain process control calculations. Moreover, licensing examinations typically include aerobic digester problems for determining volatile solids loading, digestion time, digester efficiency, and pH adjustment. These process control calculations are explained in the following sections:

18.13.3.1.1.1 Volatile Solids Loading

Volatile solids loading for the aerobic digester is expressed in pounds of volatile solids entering the digester per day per cubic foot of digester capacity:

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$$\text{Volatile Solids Loading } \left(\text{lb/d/ft}^3\right) = \frac{\text{Volatile Solids Added } (\text{lb/d})}{\text{Digester Volume } \left(\text{ft}^3\right)} \quad (18.70)$$

EXAMPLE 18.74

Problem:

The aerobic digester is 25 ft in diameter and has an operating depth of 24 ft. The sludge added to the digester daily contains 1350 lb of volatile solids. What is the volatile solids loading in pounds per day per cubic foot?

Solution:

$$\text{Volatile Solids Loading } \left(\text{lb/d/ft}^3\right) = \frac{1350 \text{ lb/d}}{0.785 \times 25 \text{ ft} \times 25 \text{ ft} \times 24 \text{ ft}} = 0.11 \text{ lb/d/ft}^3$$

18.13.3.1.1.2 Digestion Time

Digestion time is the theoretical time the sludge remains in the aerobic digester:

$$\text{Digestion Time } (\text{d}) = \frac{\text{Digester Volume } (\text{gal})}{\text{Sludge Added } (\text{gal/d})} \quad (18.71)$$

EXAMPLE 18.75

Problem:

Digester volume is 240,000 gal. Sludge is being added to the digester at the rate of 13,500 gal/d. What is the digestion time in days?

Solution:

$$\text{Digestion Time } (\text{d}) = \frac{240{,}000 \text{ gal}}{13{,}500 \ (\text{gal/d})} = 17.8 \text{ d}$$

18.13.3.1.1.3 Digester Efficiency

To determine digester efficiency or the percentage of reduction, a two-step procedure is required. The percent volatile matter reduction must first be calculated and then the percent moisture reduction:

1. Percent volatile matter reduction —Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\%\text{ Matter Reduction} = \frac{\left(\%\text{ Volatile Matter}_{in} - \%\text{ Volatile Matter}_{out}\right) \times 100}{\left[\%\text{ Vol. Matter}_{in} - \left(\%\text{ Vol. Matter}_{in} \times \%\text{ Vol. Matter}_{out}\right)\right]} \quad (18.72)$$

EXAMPLE 18.76

Problem:

Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Data:

Raw sludge volatile matter = 71%
Digested sludge volatile matter = 53%

$$\%\text{VM Reduction} = \frac{[0.71 - 0.53] \times 100}{[0.71 - (0.71 \times 0.53)]} = 53.9\% \text{ or } 54\%$$

2. Moisture reduction — Use Equation 18.73 to calculate percent moisture reduction:

$$\%\text{Moisture Reduction} = \frac{\left[\%\text{Moisture}_{in} - \%\text{Moisture}_{out}\right] \times 100}{\left[\%\text{Moisture}_{in} - \left(\%\text{Moisture}_{in} \times \%\text{Moisture}_{out}\right)\right]} \quad (18.73)$$

EXAMPLE 18.77

Problem:

Using the digester data provided below, determine the %moisture reduction for the digester (Note: %Moisture = 100% – Percent Solids):

Solution:

Raw Sludge	%Solids	6%
	%Moisture	94% (100% – 6%)
Digested Sludge	%Solids	15%
	%Moisture	85% (100% – 15%)

$$\%\text{Moisture Reduction} = \frac{[0.94 - 0.85] \times 100}{[0.94 - (0.94 \times 0.85)]} = 64\%$$

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18.13.3.1.1.4 pH Adjustment

Occasionally, the pH of the aerobic digester will fall below the levels required for good biological activity. When this occurs, the operator must perform a laboratory test to determine the amount of alkalinity required to raise the pH to the desired level. The results of the lab test must then be converted to the actual quantity of chemical (usually lime) required by the digester:

$$\text{Chem. Required, lbs} = \frac{\text{Chemical Used in Lab Test, mg}}{\text{Sample Volume, Liters}} \times \text{Dig. Vol, MG} \times 8.34\ \text{lb/gal} \quad (18.74)$$

EXAMPLE 18.78

Problem:

The lab reports that it took 225 mg of lime to increase pH of a 1-L sample of the aerobic digester contents to pH 7.2. The digester volume is 240,000 gal. How many pounds of lime will be required to increase the digester pH to 7.2?

Solution:

Chemical Required

$$= \frac{225\ \text{mg} \times 240{,}000\ \text{gal} \times 3.785\ \text{L/gal}}{1\ \text{L} \times 454\ \text{g} \times 1000\ \text{mg/g}}$$

$$= 450\ \text{lb}$$

18.13.3.2 Anaerobic Digestion

Anaerobic digestion is the traditional method of sludge stabilization. It involves using bacteria that thrive in the absence of oxygen and is slower than aerobic digestion. The advantage of anaerobic digestion is that only a small percentage of the wastes are converted into new bacterial cells. Most of the organics are converted into carbon dioxide and methane gas.

Note: In an anaerobic digester, the entrance of air should be prevented because of the potential for air mixed with the gas produced in the digester that could create an explosive mixture.

Equipment used in anaerobic digestion includes a sealed digestion tank with either a fixed or a floating cover (see Figure 18.14), heating and mixing equipment, gas storage tanks, solids and supernatant withdrawal equipment, and safety equipment (e.g., vacuum relief, pressure relief, flame traps, explosion proof electrical equipment).

In operation, process residual (thickened or unthickened sludge) is pumped into the sealed digester. The organic matter digests anaerobically by a two-stage process. Sugars, starches, and carbohydrates are converted to volatile acids, carbon dioxide, and hydrogen sulfide. The volatile acids are then converted to methane gas. This operation can occur in a single tank (single stage) or in two tanks (two stages). In a single-stage system, supernatant and digested solids must be removed whenever flow is added. In a two-stage operation, solids and liquids from the first stage flow into the second stage each time fresh solids are added. Supernatant is withdrawn from the second stage to provide additional treatment space. Solids are periodically withdrawn for dewatering or disposal. The methane gas produced in the process may be used for many plant activities.

Note: The primary purpose of a secondary digester is to allow for solids separation.

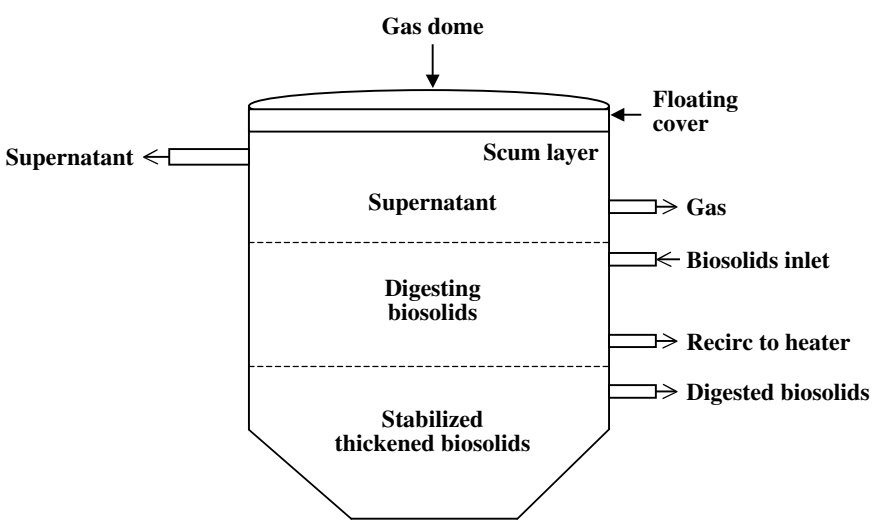

FIGURE 18.14 Floating cover anaerobic digester. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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TABLE 18.11
Anaerobic Digester — Sludge Parameters

Raw Sludge Solids	Impact
<4% Solids	Loss of alkalinity; decreased SRT; increased heating requirements; decreased volatile acids-alkalinity ratio
4–8% Solids	Normal operation
>8% Solids	Poor mixing; organic overloading; decreased volatile acids-alkalinity ratio

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

Various performance factors affect the operation of the anaerobic digester. For example, percent volatile matter in raw sludge, digester temperature, mixing, volatile acids-alkalinity ratio, feed rate, percent solids in raw sludge and pH are all important operational parameters that the operator must monitor.

Along with being able to recognize normal and abnormal anaerobic digester performance parameters, wastewater operators must also know and understand normal operating procedures. Normal operating procedures include sludge additions, supernatant withdrawal, sludge withdrawal, pH control, temperature control, mixing, and safety requirements. Important performance parameters are listed in Table 18.11.

18.13.3.2.1 Sludge Additions

Sludge must be pumped (in small amounts) several times each day to achieve the desired organic loading and optimum performance.

Note: Keep in mind that in fixed cover operations additions must be balanced by withdrawals. If not, structural damage occurs.

18.13.3.2.2 Supernatant Withdrawal

Supernatant withdrawal must be controlled for maximum sludge retention time. When sampling, sample all drawoff points and select level with the best quality.

18.13.3.2.3 Sludge Withdrawal

Digested sludge is withdrawn only when necessary. Always leave at least 25% seed.

18.13.3.2.4 pH Control

pH should be adjusted to maintain 6.8 to 7.2 pH by adjusting feed rate, sludge withdrawal, or alkalinity additions.

Note: The buffer capacity of an anaerobic digester is indicated by the volatile acid/alkalinity relationship. Decreases in alkalinity cause a corresponding increase in ratio.

18.13.3.2.5 Temperature Control

If the digester is heated, the temperature must be controlled to a normal temperature range of 90 to 95°F. Never adjust the temperature by more than 1°F per day.

18.13.3.2.6 Mixing

If the digester is equipped with mixers, mixing should be accomplished to ensure organisms are exposed to food materials.

18.13.3.2.7 Safety

Anaerobic digesters are inherently dangerous; several catastrophic failures have been recorded. To prevent such failures, safety equipment such as pressure relief and vacuum relief valves, flame traps, condensate traps, and gas collection safety devices are installed. It is important that these critical safety devices be checked and maintained for proper operation.

Note: Because of the inherent danger involved with working inside anaerobic digesters, they are automatically classified as permit-required confined spaces. All operations involving internal entry must be made in accordance with OSHA's confined space entry standard.

18.13.3.2.8 Process Control Monitoring, Testing, and Troubleshooting

During operation, anaerobic digesters must be monitored and tested to ensure proper operation. Testing should be accomplished to determine supernatant pH, volatile acids, alkalinity, BOD or COD, total solids and temperature. Sludge (in and out) should be routinely tested for percent solids and percent volatile matter. Normal operating parameters are listed in Table 18.12.

18.13.3.2.9 Anaerobic Digester: Troubleshooting

As with all other unit processes, the wastewater operator is expected to recognize problematic symptoms with anaerobic digesters and effect the appropriate corrective actions. Symptoms, causes, and corrective actions are discussed below.

1. Symptom 1: Digester gas production is reduced, pH drops below 6.8, and volatile acids-alkalinity ratio increases.
   A. Causes:
      1. Digester souring.
      2. Organic overloading.
      3. Inadequate mixing.
      4. Low alkalinity.
      5. Hydraulic overloading.
      6. Toxicity.
      7. Loss of digestion capacity.
   B. Corrective actions:
      1. Add alkalinity (digested sludge, lime, etc.).
      2. Improve temperature control.

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TABLE 18.12
Anaerobic Digester: Normal Operating Ranges

Parameter	Normal Range
Sludge retention time	
Heated	30–60 d
Unheated	180+ d
Volatile solids loading	0.04–0.1 lb VM/day/ft^3
Operating temperature	
Heated	90–95°F
Unheated	Varies with season
Mixing	
Heated (primary)	Yes
Unheated (secondary)	No
%Methane in gas	60– 72%
%Carbon dioxide in gas	28–40%
pH	6.8–7.2
Volatile acids-alkalinity ratio	≤0.1
Volatile solids reduction	40–60%
Moisture reduction	40–60%

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

3. Improve mixing.
4. Eliminate toxicity.
5. Clean digester.

2. Symptom 2: Gray foam oozing from digester.
   A. Cause:
      1. Rapid gasification.
      2. Foam producing organisms present.
      3. Foam producing chemical present.
   B. Corrective actions:
      1. Reduce mixing.
      2. Reduce feed rate.
      3. Mix slowly by hand.
      4. Clean all contaminated equipment.

18.13.3.2.10 Anaerobic Digester: Process Control Calculations

Process control calculations involved with anaerobic digester operation include determining the required seed volume, volatile acid-alkalinity ratio, SRT, estimated gas production, volatile matter reduction, and percent moisture reduction in digester sludge. Examples on how to make these calculations are provided in the following sections.

18.13.3.2.10.1 Required Seed Volume in Gallons

Use Equation 18.75 to calculate the require seed volume in gallons:

$$\text{Seed Volume (gal)} = \text{Digester Volume} \times \%\text{Seed} \quad (18.75)$$

TABLE 18.13

Operating Condition	Volatile Acids-Alkalinity Ratio
Optimum	≤0.1
Acceptable range	0.1–0.3
%Carbon dioxide in gas increases	≥0.5
pH decreases	≥0.8

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

EXAMPLE 18.79

Problem:

The new digester requires a 25% seed to achieve normal operation within the allotted time. If the digester volume is 266,000 gal, how many gallons of seed material will be required?

Solution:

$$\text{Seed Volume (gal)} = 266{,}000 \times 0.25$$
$$= 66{,}500 \text{ gal}$$

18.13.3.2.10.2 Volatile Acids-Alkalinity Ratio

The volatile acids-alkalinity ratio can be used to control operation of an anaerobic digester:

$$\text{Acids: Alkalinity Ratio} = \frac{\text{Volatile Acids Concentration}}{\text{Alkalinity Concentration}} \quad (18.76)$$

EXAMPLE 18.80

Problem:

The digester contains 240 mg/L volatile acids and 1860 mg/L alkalinity. What is the volatile acids-alkalinity ratio?

$$\text{Acids: Alkalinity Ratio} = \frac{240 \text{ mg/L}}{1860 \text{ mg/L}} = 0.13$$

Increases in the ratio normally indicate a potential change in the operation condition of the digester as shown in Table 18.13.

18.13.3.2.10.3 Sludge Retention Time

SRT is the length of time the sludge remains in the digester:

$$\text{SRT (d)} = \frac{\text{Digester Volume (gal)}}{\text{Sludge Volume Added per Day (gal/d)}} \quad (18.77)$$

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EXAMPLE 18.81

Problem:

Sludge is added to a 525,000-gal digester at the rate of 12,250 gal/d. What is the sludge retention time?

Solution:

$$\text{SRT (d)} = \frac{525{,}000 \text{ gal}}{12{,}250 \text{ gal/d}} = 42.9 \text{ d}$$

18.13.3.2.10.4 Estimated Gas Production

The rate of gas production is normally expressed as the volume of gas (ft^3) produced per pound of volatile matter destroyed. The total cubic feet of gas a digester will produce per day can be calculated by:

$$\text{Gas Production } \left(\text{ft}^3/\text{d}\right) = \text{VM}_{\text{in}} \left(\text{lb/d}\right) \times \text{\%VM Reduction} \times \text{Production Rate } \left(\text{ft}^3/\text{lb}\right) \tag{18.78}$$

EXAMPLE 18.82

Problem:

The digester receives 11,450 lb of volatile matter per day. The volatile matter reduction achieved by the digester is 52%. The rate of gas production is 11.2 ft^3 of gas per pound of volatile matter destroyed. What is the estimated gas production per day?

Solution:

$$\text{Gas Production } \left(\text{ft}^3/\text{d}\right) = 11{,}450 \text{ lb/d} \times 0.52 \times 11.2 \text{ ft}^3/\text{lb} = 66{,}685 \text{ ft}^3/\text{d}$$

18.13.3.2.10.5 Percent Volatile Matter Reduction

Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\text{\% Reduction} = \frac{\left(\text{\% Volatile Matter}_{\text{in}} - \text{\% Volatile Matter}_{\text{out}}\right) \times 100}{\left[\text{\% Volatile Matter}_{\text{in}} - \left(\text{\% Volatile Matter}_{\text{in}} \times \text{\% Volatile Matter}_{\text{out}}\right)\right]} \tag{18.79}$$

EXAMPLE 18.83

Problem:

Using the digester data provided below, determine the percent volatile matter reduction for the digester.

Data:

Raw sludge volatile matter = 74%
Digested sludge volatile matter = 55%

$$\text{\%VM Reduction} = \frac{[0.74 - 0.55] \times 100}{[0.74 - (0.74 \times 0.55)]} = 57\%$$

18.13.3.2.10.6 Percent Moisture Reduction in Digested Sludge

Use Equation 18.92 to calculate the percent moisture reduction in digested sludge:

$$\text{\%Moisture Reduction} = \frac{\left[\text{\%Moisture}_{\text{in}} - \text{\%Moisture}_{\text{out}}\right] \times 100}{\left[\text{\%Moisture}_{\text{in}} - \left(\text{\%Moisture}_{\text{in}} \times \text{\%Moisture}_{\text{out}}\right)\right]} \tag{18.80}$$

EXAMPLE 18.84

Problem:

Using the digester data provided below, determine the percent moisture reduction and percent volatile matter reduction for the digester (Note: %Moisture = 100% – Percent Solids):

Solution:

Raw sludge %solids = 6%
Digested sludge %solids = 14%

$$\text{\%Moisture Reduction} = \frac{[0.94 - 0.86] \times 100}{[0.94 - (0.94 \times 0.86)]} = 61\%$$

18.13.3.3 Other Sludge Stabilization Processes

Along the aerobic and anaerobic digestion, other sludge stabilization processes include composting, lime stabilization, wet air oxidation, and chemical (chlorine) oxidation. These other stabilization processes are briefly described in this section.

18.13.3.3.1 Composting

The purpose of composting sludge is to stabilize the organic matter, reduce volume, and eliminate pathogenic organisms. In a composting operation, dewatered solids are usually mixed with a bulking agent (i.e., hardwood chips) and stored until biological stabilization occurs. The composting mixture is ventilated during storage to provide sufficient oxygen for oxidation and to prevent odors. After the solids are stabilized, they are separated from the bulking agent. The composted solids are then stored for curing and applied to farmlands or other beneficial uses. Expected performance of the composting operation for

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both percent volatile matter reduction and percent moisture reduction ranges from 40 to 60%+.

18.13.3.3.2 Lime Stabilization

In lime stabilization, process residuals are mixed with lime to achieve a pH of 12. This pH is maintained for at least 2 h. The treated solids can then be dewatered for disposal or directly land applied.

18.13.3.3.3 Thermal Treatment

Thermal treatment (or wet air oxidation) subjects sludge to high temperature and pressure in a closed reactor vessel. The high temperature and pressure rupture the cell walls of any microorganisms present in the solids and causes chemical oxidation of the organic matter. This process substantially improves dewatering and reduces the volume of material for disposal. It also produces a very high strength waste, which must be returned to the wastewater treatment system for further treatment.

18.13.3.3.4 Chlorine Oxidation

Chlorine oxidation also occurs in a closed vessel. In this process, chlorine (100 to 1000 mg/L) is mixed with a recycled solids flow. The recycled flow and process residual flow are mixed in the reactor. The solids and water are separated after leaving the reactor vessel. The water is returned to the wastewater treatment system and the treated solids are dewatered for disposal. The main advantage of chlorine oxidation is that it can be operated intermittently. The main disadvantage is production of extremely low pH and high chlorine content in the supernatant.

18.13.3.3.5 Stabilization: Operation and Performance

Depending on the stabilization process employed, the operational components vary. In general, operations include pumping, observations, sampling and testing, process control calculations, maintenance, and housekeeping. Performance of the stabilization process will also vary with the type of process used. Stabilization processes can generally produce 40 to 60% reduction of both volatile matter (organic content) and moisture.

18.13.4 Sludge Dewatering

Digested sludge removed from the digester is still mostly liquid. *Sludge dewatering* is used to reduce volume by removing the water to permit easy handling and economical reuse or disposal. Dewatering processes include sand drying beds, vacuum filters, centrifuges, filter presses (belt and plate), and incineration.

18.13.4.1 Sand Drying Beds

Drying beds have been used successfully for years to dewater sludge. Composed of a sand bed (consisting of a gravel base, underdrains, and 8 to 12 in. of filter grade sand), drying beds include an inlet pipe, splash pad containment walls, and a system to return filtrate (water) for treatment. In some cases, the sand beds are covered to provide drying solids protection from the elements.

In operation, solids are pumped to the sand bed and allowed to dry by first draining off excess water through the sand and then by evaporation. This is the simplest and cheapest method for dewatering sludge. No special training or expertise is required. There is a downside; drying beds require a great deal of manpower to clean beds, they can create odor and insect problems, and they can cause sludge buildup during inclement weather.

18.13.4.1.1 Performance Factors

In sludge drying beds, various factors affect the length of time required to achieve the desired solids concentrations. The major factors and their impact on drying bed performance include the following:

1. Climate — Drying beds in cold or moist climates will require significantly longer drying time to achieve an adequate level of percent solids concentrations in the dewatered sludge.
2. Depth of applied sludge — The depth of the sludge drawn onto the bed has a major impact on the required drying time. Deeper sludge layers require longer drying times. Under ideal conditions, a well-digested sludge drawn to a depth of approximately 8 in. will require approximately 3 weeks to reach the desired 40 to 60% solids.
3. Type of sludge applied — The quality and solids concentration of the drying media will affect the time requirements.
4. Bed cover — Covered-drying beds prevent rewetting of the sludge during storm events. In most cases, this reduces the average drying time required to reach the desired solids levels.

18.13.4.1.2 Operation, Observation, and Troubleshooting Procedures

Although drying beds involve two natural processes — drainage and evaporation — that normally work well enough on their own, a certain amount of preparation and operator attention is still required to maintain optimum drying performance. For example, in the preparation stage, all debris is removed from the raked and leveled media surface. Then, all openings to the bed are sealed.

After the bed is properly prepared, the sludge lines are opened, and sludge is allowed to flow slowly onto the media. The bed is filled to desired operating level (8 to 12 in.). The sludge line is closed and flushed, and the bed drain is opened. Water begins to drain. The sludge remains on the media until the desired percent solids (40 to 60%) is achieved. Later, the sludge is removed. In most operations,

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manual removal is required to prevent damage to the underdrain system. The sludge is disposed of in an approved landfill or by land application as a soil conditioner.

18.13.4.1.3 Operational Problems

In the operation of a sludge drying bed, the operator observes the operations and looks for various indicators of operational problems and makes process adjustments as required:

1. Sludge takes a long time to dewater.
   A. Causal factors:
      1. Applied sludge is too deep.
      2. Sludge was applied to a dirty bed.
      3. The drain system is plugged or broken.
      4. Insufficient design capacity.
      5. Inclement weather or poor drying conditions.
   B. Corrective actions (where applicable):
      1. Allow bed to dry to minimum acceptable % solids and remove.
      2. Use described procedure below to determine appropriate sludge depth.
         a. Clean bed and apply smaller depth of sludge (i.e., 6 to 8 in.).
         b. Measure the decrease in depth (drawdown) at the end of 3 days of drying.
         c. Use a sludge depth equal to twice the 3-d drawdown depth for future applications.
      3. After sludge has dried, remove sludge and 0.5 to 1.0 in. of sand. Add clean sand.
      4. Allow sludge to dry to minimum allowable percent solids and remove.
      5. Use external water source (with back flow prevention) to slowly flush underdrains.
      6. Repair or replace underdrains as required.
      7. Prevent damage to underdrains by draining during freezing weather.
      8. Use polymer to increase bed performance.
      9. Cover or enclose the beds.
2. Influent sludge is very thin.
   A. Causal factor:
      1. Coning is occurring in the digester.
   B. Corrective action:
      1. Reduce rate of sludge withdrawal.
3. Sludge feed lines plug frequently.
   A. Causal factor:
      1. Solids or grit is accumulating in the line.
   B. Corrective actions:
      1. Open lines fully at the start of each withdrawal cycle.
      2. Flush lines at the end of each withdrawal cycle.
4. Flies breeding in the drying sludge.
   A. Causal factors:
      1. Inadequately digested sludge.
      2. Natural insect reproduction.
   B. Corrective actions:
      1. Break sludge crust and apply a larvicide (borax).
      2. Use insecticide (if approved) to remove adult insects.
      3. Remove sludge as soon as possible.
5. Objectionable odors are present when sludge is applied to bed.
   A. Causal factor:
      1. Raw or partially digested sludge is being applied to the bed.
   B. Corrective actions:
      1. Add lime to the sludge to control odors and potential insect and rodent problems.
      2. Remove the sludge as quickly as possible.
      3. Identify and correct the digester problem.

18.13.4.2 Rotary Vacuum Filtration

Rotary vacuum filters have also been used for many years to dewater sludge. The vacuum filter includes filter media (belt, cloth or metal coils), media support (drum), vacuum system, chemical feed equipment, and conveyor belts to transport the dewatered solids.

In operation, chemically treated solids are pumped to a vat or tank in which a rotating drum is submerged. As the drum rotates, a vacuum is applied to the drum. Solids collect on the media and are held there by the vacuum as the drum rotates out of the tank. The vacuum removes additional water from the captured solids. When solids reach the discharge zone, the vacuum is released and the dewatered solids are discharged onto a conveyor belt for disposal. The media are then washed prior to returning to the start of the cycle.

18.13.4.2.1 Types of Rotary Vacuum Filters

The three principal types of rotary vacuum filters are rotary drum, coil, and belt.

The rotary drum filter consists of a cylindrical drum rotating partially submerged in a vat or pan of conditioned sludge. The drum is divided length-wise into a number of sections that are connected through internal piping to ports in the valve body (plant) at the hub. This plate rotates in contact with a fixed valve plate with similar parts that are connected to a vacuum supply, a compressed air supply, and an atmosphere vent. As the drum rotates, each section is connected to the appropriate service.

The coil type vacuum filter uses two layers of stainless steel coils arranged in corduroy fashion around the drum. After a dewatering cycle, the two layers of springs leave the drum bed and are separated from each other so that

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the cake is lifted off the lower layer and is discharged from the upper layer. The coils are then washed and reapplied to the drum. The coil filter is used successfully for all types of sludges; sludges that have extremely fine particles or are resistant to flocculation de-water poorly with this system.

The media on a belt filter leave the drum surface at the end of the drying zone and passes over a small diameter discharge roll to aid cake discharge. Washing of the media occurs next. Then the media are returned to the drum and to the vat for another cycle. This type of filter normally has a small-diameter curved bar between the point where the belt leaves the drum and the discharge roll. This bar primarily aids in maintaining belt dimensional stability.

18.13.4.2.1.1 Filter Media

Drum and belt vacuum filters use natural or synthetic fiber materials. On the drum filter, the cloth is stretched and secured to the surface of the drum. In the belt filter, the cloth is stretched over the drum and through the pulley system. The installation of a blanket requires several days. The cloth will (with proper care) last several hundred to several thousand hours. The life of the blanket depends on the cloth selected, the conditioning chemical, backwash frequency, and cleaning (i.e., acid bath) frequency.

18.13.4.2.1.2 Filter Drum

The filter drum is a maze of pipe work running from a metal screen and wooden skeleton and connecting to a rotating valve port at each end of the drum. The drum is equipped with a variable speed drive to turn the drum from 1/8 to 1 r/min. Normally, solids pickup is indirectly related to the drum speed. The drum is partially submerged in a vat containing the conditioned sludge. Normally, submergence is limited to 1/5 or less of filter surface at a time.

18.13.4.2.1.3 Chemical Conditioning

Sludges that are dewatered using vacuum filtration are normally chemically conditioned just prior to filtration. Sludge conditioning increases the percentage of solids captured by the filter and improves the de-watering characteristics of the sludge. Conditional sludge must be filtered as quickly as possible after chemical addition to obtain these desirable results.

18.13.4.2.2 Operation, Observation, and Troubleshooting Procedures

In operation, the rotating drum picks up chemically treated sludge. A vacuum is applied to the inside of the drum to draw the sludge onto the outside of the drum cover. This porous outside cover or filter medium allows the filtrate or liquid to pass through into the drum and the filter cake (dewatered sludge) to stay on the medium. In the cake release or discharge mode, slight air pressure is applied to the drum interior. Dewatered solids are lifted from the medium and scraped off by a scraper blade. Solids drop onto a conveyor for transport for further treatment or disposal. The filtrate water is returned to the plant for treatment.

While in operation, the operator observes drum speed, sludge pickup, filter cake thickness and appearance, chemical feed rates, sludge depth in vat, and overall equipment operation. Sampling and testing are routinely performed on influent sludge solids concentration, filtrate BOD and solids, and sludge cake solids concentration. We cover the indicators and observations of vacuum filter operational problems and causal factors, along with recommended corrective actions in the following list:

1. High solids in filtrate.
   A. Causal factors:
      1. Improper coagulant dosage.
      2. Filter media binding.
   B. Corrective actions (where applicable):
      1. Adjust coagulant dosage.
      2. Recalibrate coagulant feeder.
      3. Clean synthetic cloth with steam and detergent.
      4. Clean steel coil with acid bath.
      5. Clean cloth with water or replace cloth.
2. Thin filter cake and poor dewatering.
   A. Causal factors:
      1. Filter media binding.
      2. Improper chemical dosage.
      3. Inadequate vacuum.
      4. Drum speed is too high.
      5. Drum submergence is too low.
   B. Corrective actions (where applicable):
      1. Clean synthetic cloth with steam and detergent.
      2. Clean steel cloth with acid bath.
      3. Clean cloth with water or replace cloth.
      4. Adjust coagulant dosage.
      5. Recalibrate coagulant feeder.
      6. Repair vacuum system.
      7. Reduce drum speed.
      8. Increase drum submergence.
3. Vacuum pump stops.
   A. Causal factors:
      1. Power to drive motor is off.
      2. Lack of seal water.
      3. Broken drive belt.
   B. Corrective action (where applicable):
      1. Reset heater, breaker, etc. and restart.
      2. Starts seal water flow.
      3. Replace drive belt.
4. Drum stops rotating.
   A. Causal factor:
      1. Power to drive motor is off.
   B. Corrective action:
      1. Reset heater, breaker, etc. and restart
5. Receiver vibrating.

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A. Causal factors:
   1. Filtrate pump is clogged.
   2. Loose bolts and gasket around inspection plate.
   3. Worn ball check valve in filtrate pump.
   4. Air leaks in suction line.
   5. Dirty drum face.
   6. Seal strips are missing.
B. Corrective actions (where applicable):
   1. Clear pump.
   2. Tighten bolts and gasket.
   3. Replace ball check.
   4. Seal leaks.
   5. Clean face with pressure hose.
   6. Replace missing seal strips.

6. High vat level.
   A. Causal factors:
      1. Improper chemical conditioning.
      2. Feed Rate is too high.
      3. Drum speed is too slow.
      4. Filtrate pump is off or clogged.
      5. Drain line is plugged.
      6. Vacuum pump has stopped.
      7. Seal strips are missing.
   B. Corrective actions:
      1. Change coagulant dosage.
      2. Reduce feed rate.
      3. Increase drum speed.
      4. Turn on or clean pump.
      5. Clean drain line.
      6. Replace seal strips.
7. Low vat level.
   A. Causal factors:
      1. Feed rate is too low.
      2. Vat drain valve is open.
   B. Corrective actions (where applicable):
      1. Increase feed rate.
      2. Close vat drain valve.
8. Vacuum pump is drawing high amperage.
   A. Causal factors:
      1. Filtrate pump is clogged.
      2. Improper chemical conditioning.
      3. High vat level.
      4. Cooling water flow to vacuum pump is too high.
   B. Corrective actions (where applicable):
      1. Clear pump clog.
      2. Adjust coagulant dosage.
      3. Decrease cooling water flow rate.
9. Scale buildup on vacuum pump seals.
   A. Causal factor:
      1. Hard, unstable water.
   B. Corrective action:
      1. Add sequestering agent.

18.13.4.2.3 Process Control Calculations

Probably the most frequent calculation vacuum filter operators have to make is for determining filter yield. Example 18.85 illustrates how this calculation is made.

18.13.4.2.3.1 Filter Yield: Vacuum Filter

EXAMPLE 18.85

Problem:

Thickened thermally conditioned sludge is pumped to a vacuum filter at a rate of 50 gal/min. The vacuum area of the filter is 12 ft wide with a drum diameter of 9.8 ft. If the sludge concentration is 12%, what is the filter yield in pounds per hour per square foot? Assume the sludge weighs 8.34 lb/gal.

Solution:

Calculate the filter surface area:

$$\text{Area of a cylinder side} = 3.14 \times \text{Diameter} \times \text{Length}$$

$$= 3.14 \times 9.8\ \text{ft} \times 12\ \text{ft}$$

$$= 369.3\ \text{ft}^2$$

Calculate the pounds of solids per hour:

$$50\ \text{gal/min} \times 60\ \text{min/h} \times 8.34\ \text{lb/gal} \times 0.12 =$$

$$3002.4\ \text{lb/h}$$

Divide the two results:

$$\frac{3002.4\ \text{lb/h}}{369.3\ \text{ft}^2} = 8.13\ \text{lb/h/ft}^2$$

18.13.4.3 Pressure Filtration

Pressure filtration differs from vacuum filtration in that the liquid is forced through the filter media by a positive pressure instead of a vacuum. Several types of presses are available, but the most commonly used types are plate and frame presses and belt presses.

Filter presses include the belt or plate and frame types. The belt filter includes two or more porous belts, rollers, and related handling systems for chemical makeup and feed. It also includes supernatant and solids collection and transport (see Figure 18.15).

The plate and frame filter consists of a support frame, filter plates covered with porous material, hydraulic or mechanical mechanism for pressing plates together, and related handling systems for chemical makeup and feed. It also includes supernatant and solids collection and transport.

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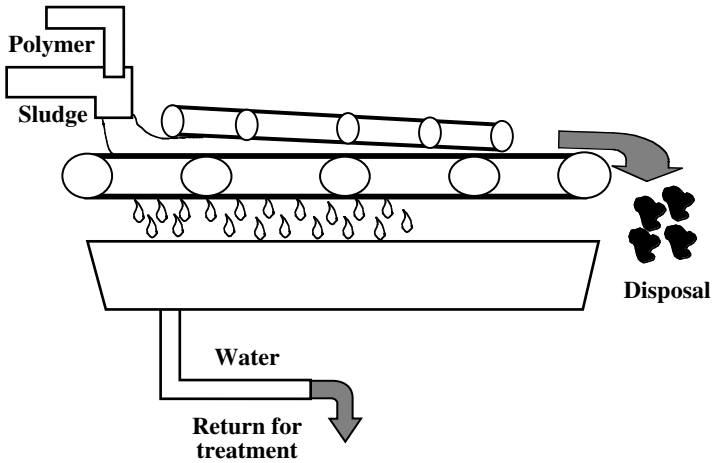

FIGURE 18.15 Belt filter press. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

In the plate and frame filter, solids are pumped (sandwiched) between plates. Pressure (200 to 250 psi) is applied to the plates and water is squeezed from the solids. At the end of the cycle, the pressure is released and as the plates separate the solids drop out onto a conveyor belt for transport to storage or disposal.

Performance factors for plate and frame presses include feed sludge characteristics, type and amount of chemical conditioning, operating pressures, and the type and amount of precoat.

In operation, the belt filter uses a coagulant (polymer) mixed with the influent solids. The chemically treated solids are discharged between two moving belts. First water drains from the solids by gravity. The two belts then move between a series of rollers, and pressure squeezes additional water out of the solids. The solids are then discharged onto a conveyor belt for transport to storage or disposal.

Performance factors for the belt press include sludge feed rate, belt speed, belt tension, belt permeability, chemical dosage, and chemical selection.

Filter presses have lower operation and maintenance costs than vacuum filters or centrifuges. They typically produce a good quality cake and can be batch operated. The downside is that construction and installation costs are high. Moreover, chemical addition is required and the presses must be operated by skilled personnel.

18.13.4.3.1 Operation, Observation, and Troubleshooting Procedures

Most plate and filter press operations are partially or fully automated. Operation consists of observation, maintenance, and sampling and testing.

Operation of belt filter presses consists of preparation of conditioning chemicals, chemical feed rate adjustments, sludge feed rate adjustments, belt alignment, belt speed and belt tension adjustments, sampling and testing, and maintenance.

We include common operational problems, causal factors, and recommended corrective actions for the plate press and belt filter press in the following list.

Plate Press

1. Plates fail to seal.
   A. Causal factors:
      1. Poor alignment.
      2. Inadequate shimming.
   B. Corrective actions (where applicable):
      1. Realign parts.
      2. Adjust shimming of stay bosses.
2. Cake discharge is difficult.
   A. Causal factors:
      1. Inadequate precoat.
      2. Improper conditioning.
   B. Corrective actions (where applicable):
      1. Increase precoat and feed at 25 to 40 psig.
      2. Change conditioner type or dosage (use filter leaf test to determine).
3. Filter cycle times are excessive.
   A. Causal factors:
      1. Improper conditioning.
      2. Feed solids are low.
   B. Corrective Actions (where applicable):
      1. Change chemical dosage.
      2. Improve thickening operation.
4. Filter cake sticks to conveyors.
   A. Causal factor:
      1. Improper conditioning chemical or dosage.
   B. Corrective action:
      1. Increase inorganic conditioner dose.
5. Precoat pressures gradually increase.
   A. Causal factors:
      1. Improper sludge conditioning.
      2. Improper precoat feed.

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3. Filter media plugged.
4. Calcium buildup in media.

B. Corrective actions (where applicable):
1. Change chemical dosage
2. Decrease feed for a few cycles and optimize.
3. Wash filter media.
4. Wash media with inhibited hydrochloric acid.

6. Frequent media binding.
A. Causal factors:
1. Inadequate precoat.
2. Initial feed rate too high (no precoat).

B. Corrective actions (where applicable):
1. Increase precoat.
2. Reduce feed rate or develop initial cake slowly.

7. Excessive moisture in cake.
A. Causal factors:
1. Improper conditioning.
2. Filter cycle too short.

B. Corrective actions (where applicable):
1. Change chemical dosage.
2. Lengthen filter cycle.

8. Sludge blowing out of press.
A. Causal factor:
1. Obstruction between plates.

B. Corrective Action:
1. Shut down feed pump, hit press closure drive, restart feed pump, and clean after cycle.

9. Plate Press: Leaks around Lower Faces of Plates
A. Causal factor:
1. Wet cake soiling media on lower faces.

B. Corrective actions (where applicable):
1. Change chemical dosage.
2. Lengthen filter cycle.

Belt Press

1. Filter cake discharge is difficult.
A. Causal factors:
1. Wrong conditioning chemical selected.
2. Improper chemical dosage.
3. Changing sludge characteristics.
4. Wrong application point.

B. Corrective actions (where applicable):
1. Change conditioning chemical.
2. Adjust chemical dosage.
3. Change chemical or sludge
4. Adjust application point.

2. Sludge leaking from belt edges.
A. Causal factors:
1. Excessive belt tension.
2. Belt speed too low.
3. Excessive sludge feed rate.

B. Corrective actions (where applicable):
1. Reduce belt tension.
2. Increase belt speed.
3. Reduce sludge feed rate.

3. Excessive moisture in filter cake.
A. Causal factors:
1. Improper belt speed or drainage time.
2. Wrong conditioning chemical.
3. Improper chemical dosage.
4. Inadequate belt washing.
5. Wrong belt weave or material.

B. Corrective actions (where applicable):
1. Adjust belt speed.
2. Change conditioning chemical.
3. Adjust chemical dosage.
4. Clear spray nozzles or adjust sprays.
5. Replace belt.

4. Excessive belt wear along edges.
A. Causal factors:
1. Roller misalignment.
2. Improper belt tension.
3. Tension or alignment in control system.

B. Corrective actions (where applicable):
1. Correct roller alignment.
2. Correct tension.
3. Repair tracking and alignment system controls.

5. Belt shifts or seizes.
A. Causal factors:
1. Uneven sludge distribution.
2. Inadequate or uneven belt washing.

B. Corrective actions:
1. Adjust feed for uniform sludge distribution.
2. Clean and adjust belt-washing sprays.

18.13.4.3.2 Process Control Calculations: Filter Presses

As part of the operating routine for filter presses, operators are called upon to make certain process control calculations. The process control calculation most commonly used in operating the belt filter press determines the hydraulic loading rate on the unit. The most commonly used process control calculation used in operation of plate and filter presses determines the pounds of solids pressed per hour. Both of these calculations are demonstrated below.

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18.13.4.3.2.1 Hydraulic Loading Rate: Belt Filter Press

EXAMPLE 18.86

Problem:

A belt filter press receives a daily sludge flow of 0.30 gal. If the belt is 60 in. wide, what is the hydraulic loading rate on the unit in gallons per minute for each foot of belt width?

Solution:

$$\frac{0.30\ \text{MGD} \times 1{,}000{,}000\ \text{gal/MG}}{1440\ \text{min/d}} = 208.3\ \text{gal/min}$$

$$60\ \text{in.} \times \frac{1\ \text{ft}}{12\ \text{in.}} = 5\ \text{ft}$$

$$\frac{208.3\ \text{gal}}{5\ \text{ft}} = 41.7\ \text{gal/min/ft}$$

18.13.4.3.2.2 Pounds of Solids Pressed per Hour: Plate and Frame Press

EXAMPLE 18.87

Problem:

A plate and frame filter press can process 850 gal of sludge during its 120-min operating cycle. If the sludge concentration is 3.7%, and if the plate surface area is 140 ft^2, how many pounds of solids are pressed per hour for each square foot of plate surface area?

Solution:

$$850\ \text{gal} \times 0.037 \times 8.34\ \text{lb/gal} = 262.3\ \text{lb}$$

$$\frac{262.3\ \text{lb}}{120\ \text{min}} \times \frac{60\ \text{min}}{1\ \text{h}} = 131.2\ \text{lb/h}$$

$$\frac{131.2\ \text{lb/h}}{140\ \text{ft}^2} = 0.94\ \text{lb/h/ft}^2$$

18.13.4.4 Centrifugation

Centrifuges of various types have been used in dewatering operations for at lease 30 years and appear to be gaining in popularity. Depending on the type of centrifuge used and the centrifuge pumping equipment for solids feed and centrate removal, chemical makeup and feed equipment and support systems for removal of dewatered solids are required.

18.13.4.4.1 Operation, Observation, and Troubleshooting Procedures

Generally, the centrifuge spins at a very high speed when operating. The centrifugal force it creates throws the solids out of the water. Chemically conditioned solids are pumped into the centrifuge. The spinning action throws the solids to the outer wall of the centrifuge. The centrate (water) flows inside the unit to a discharge point. The solids held against the outer wall are scraped to a discharge point by an internal scroll moving slightly faster or slower than the centrifuge speed of rotation.

In the operation of the continuous feed, solids bowl, conveyor type centrifuge (this is the most common type currently used), and other commonly used centrifuges, solid and liquid separation occurs as a result of rotating the liquid at high speeds to cause separation by gravity.

In the solid bowl type, the solid bowl has a rotating unit with a bowl and a conveyor (see Figure 18.16). The unit has a conical section at one end that acts as a drainage device. The conveyor screw pushes the sludge solids to outlet ports and the cake to a discharge hopper. The sludge slurry enters the rotating bowl through a feed pipe leading into the hollow shaft of the rotating screw conveyor. The sludge is distributed through ports into a pool inside the rotating bowl. As the liquid sludge flows through the hollow shaft toward the overflow device, the fine solids settle to the wall of the rotating bowl. The screw conveyor pushes the solids to the conical section where the solids are forced out of the water and the water drains back in the pool.

The expected percent solids for centrifuge dewatered sludges is in the range of 10 to 15%. The expected

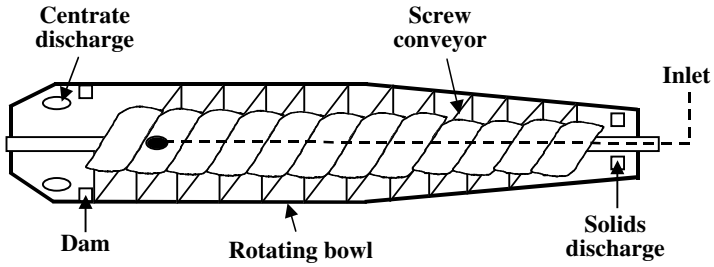

FIGURE 18.16 Centrifuge. (From Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.)

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TABLE 18.14
Expected Percent Solids for Centrifuge Dewatered Sludges

Type of Sludge	%Solids
Raw sludge	25–35%
Anaerobic digestion	15–30%
Activated sludge	8–10%
Heat treated	30–50%

Source: Spellman, F.R., *Spellman's Standard Handbook for Wastewater Operators,* Vol. 1, Technomic Publ., Lancaster, PA, 1999.

performance is depended on the type of sludge being dewatered, as shown in Table 18.14.

Centrifuge operation is dependent upon various performance factors:

1. Bowl design (length-diameter ratio and flow pattern)
2. Bowl speed
3. Pool volume
4. Conveyor design
5. Relative conveyor speed
6. Type and condition of sludge
7. Type and amount of chemical conditioning
8. Operating pool depth
9. Relative conveyor speed (if adjustable)

Centrifuge operators often find that the operation of centrifuges can be simple, clean, and efficient. In most cases, chemical conditioning is required to achieve optimum concentrations. Operators soon discover that centrifuges are noisemakers; units run at very high speed and produce high-level noise, which can cause loss of hearing with prolonged exposure. When working in an area where a centrifuge is in operation, special care must be taken to provide hearing protection.

Actual operation of a centrifugation unit requires the operator to perform the following tasks:

1. Control and adjust chemical feed rates.
2. Observe unit operation and performance.
3. Control and monitor centrate returned to treatment system.
4. Perform required maintenance as outlined in the manufacturer's technical manual.

The centrifuge operator must be trained to observe and recognize (as with other unit processes) operational problems that may occur with centrifuge operation. We cover several typical indicators and observations of centrifuge problems, along with causal factors and suggested corrective actions (troubleshooting procedures) in the following sections.

1. Poor centrate clarity.
   A. Causal factors:
      1. Feed rate is too high.
      2. Wrong plate dam position.
      3. Worn conveyor flights.
      4. Speed is too high.
      5. High feed sludge solids concentration.
      6. Improper chemical conditioning.
   B. Corrective actions (where applicable):
      1. Adjust sludge feed rate.
      2. Increase pool depth.
      3. Repair or replace conveyor.
      4. Change pulley setting to obtain lower speed.
      5. Dilute sludge feed.
      6. Adjust chemical dosage.
2. Solids cake is not dry enough.
   A. Causal factors:
      1. Feed rate is too high.
      2. Wrong plate dam position.
      3. Speed is too low.
      4. Excessive chemical conditioning.
      5. Influent is too warm.
   B. Corrective actions (if applicable):
      1. Reduce sludge feed rate.
      2. Decrease pool depth to increase dryness.
      3. Change pulley setting to obtain higher speed.
      4. Adjust chemical dosage.
      5. Reduce influent temperature.
3. Torque control keeps tripping.
   A. Causal factors:
      1. Feed rate is too high.
      2. Feed solids concentration is too high.
      3. Foreign material (i.e., tramp iron) in machine.
      4. Gear unit is misaligned.
      5. Gear unit has mechanical problem.
   B. Corrective actions (where applicable):
      1. Reduce flows.
      2. Dilute flows.
      3. Remove conveyor or clear foreign materials.
      4. Correct gear unit alignment.
      5. Repair gear unit.
4. Excess vibration.
   A. Causal factors:
      1. Improper lubrication.
      2. Improper adjustment of vibration isolators.
      3. Discharge funnels are contacting centrifuge.

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4. Portion of conveyor flights may be plugged (causing an imbalance).
5. Gear box improperly aligned.
6. Pillow box bearings are damaged.
7. Bowl is out of balance.
8. Parts are not tightly assembled.
9. Uneven wear on conveyor.

B. Corrective actions (where applicable):
1. Lubricate according to manufacturer's instructions.
2. Adjust isolators.
3. Reposition slip joints at funnels.
4. Flush centrifuge.
5. Align gearbox.
6. Replace bearings.
7. Return rotating parts to factory for rebalancing
8. Tighten parts.
9. Resurface and rebalance.

5. Sudden increase in power consumption.
A. Causal factors:
1. Contact between bowl exterior and accumulated solids in case.
2. Effluent pipe is plugged.

B. Corrective actions (where applicable):
1. Apply hard surfacing to areas with wear.
2. Clear solids discharge.

6. Gradual increase in power consumption.
A. Causal factor:
1. Conveyor blade wear.

B. Corrective action:
1. Replace blades.

7. Spasmodic surging of solids discharge.
A. Causal factors:
1. Pool depth too low.
2. Conveyor helix is rough.
3. Feed pipe too near drainage deck.
4. Excessive vibration.

B. Corrective Actions (where applicable):
1. Increase pool depth.
2. Refinish conveyor blade area.
3. Move feed pipe to effluent end.

8. Centrifuge shuts down or will not start.
A. Causal factors:
1. Blown fuses.
2. Overload relay is tripped.
3. Motor overheated or thermal protectors are tripped.
4. Torque control is tripped.
5. Vibration switch is tripped.

B. Corrective actions (where applicable):
1. Replace fuses.
2. Flush centrifuge and reset relay.
3. Flush centrifuge and reset thermal protectors.

18.13.4.5 Sludge Incineration

Not surprisingly, incinerators produce the maximum solids and moisture reductions. The equipment required depend on whether the unit is a multiple hearth or fluid-bed incinerator. Generally, the system will require a source of heat to reach ignition temperature, solids feed system and ash handling equipment. It is important to note that the system must also include all required equipment (e.g., scrubbers) to achieve compliance with air pollution control requirements.

In operation, solids are pumped to the incinerator. The solids are dried and ignited (burned). As they burn the organic matter is converted to carbon dioxide and water vapor and the inorganic matter is left behind as ash or fixed solids. The ash is then collected for reuse of disposal.

18.13.4.5.1 Process Description

The incineration process first dries then burns the sludge. The process involves the following steps:

1. The temperature of the sludge feed is raised to 212°F.
2. Water evaporates from the sludge.
3. The temperature of the water vapor and air mixture increases.
4. The temperature of the dried sludge volatile solids raises to the ignition point.

Note: Incineration will achieve maximum reductions if sufficient fuel, air, time, temperature, and turbulence are provided.

18.13.4.5.2 Incineration Processes

18.13.4.5.2.1 Multiple Hearth Furnace

The multiple hearth furnace consists of a circular steel shell surrounding a number of hearths. Scrappers (rabble arms) are connected to a central rotating shaft. Units range from 4.5 to 21.5 ft in diameter and have from 4 to 11 hearths.

In operation, dewatered sludge solids are placed on the outer edge of the top hearth. The rotating rabble arms move them slowly to the center of the hearth. At the center of the hearth, the solids fall through ports to the second level. The process is repeated in the opposite direction. Hot gases generated by burning on lower hearths dry the solids. The dry solids pass to the lower hearths. The high temperature on the lower hearths ignites the solids. Burning continues to completion. Ash materials discharge to lower cooling hearths where they are discharged for disposal. Air flowing inside center column and rabble arms continuously cools internal equipment.

18.13.4.5.2.2 Fluidized Bed Furnace

The fluidized bed incinerator consists of a vertical circular steel shell (reactor) with a grid to support a sand bed and an air system to provide warm air to the bottom of the

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sand bed. The evaporation and incineration process takes place within the super-heated sand bed layer.

In operation, air is pumped to the bottom of the unit. The airflow expands (fluidizes) the sand bed inside. The fluidized bed is heated to its operating temperature (1200 to 1500°F). Auxiliary fuel is added when needed to maintain operating temperature. The sludge solids are injected into the heated sand bed. Moisture immediately evaporates. Organic matter ignites and reduces to ash. Residues are ground to fine ash by the sand movement. Fine ash particles flow up and out of the unit with exhaust gases. Ash particles are removed using common air pollution control processes. Oxygen analyzers in the exhaust gas stack control the airflow rate.

Note: Because these systems retain a high amount of heat in the sand, the system can be operated as little as four hours per day with little or no reheating.

18.13.4.5.3 Operation, Observation, and Troubleshooting Procedures

The operator of an incinerator monitors various performance factors to ensure optimal operation. These performance factors include feed sludge volatile content, feed sludge moisture content, operating temperature, sludge feed rate, fuel feed rate, and air feed rate.

Note: To ensure that the volatile material is ignited, the sludge must be heated between 1400 and 1700°F.

In ensuring operating parameters are in the correct range, the operator monitors and adjusts sludge feed rate, airflow, and auxiliary fuel feed rate.

All maintenance conducted on an incinerator should be in accordance with manufacturer's recommendations.

18.13.4.5.3.1 Operational Problems

The operator of a multiple hearth or fluidized bed incinerator must be able to recognize operational problems using various indicators and observations. We discuss these indicators and observations, causal factors, and recommended corrective actions in the following list:

Multiple Hearths

1. Incinerator temperature is too high.
   A. Causal factors:
      1. Excessive fuel feed rate.
      2. Greasy solids.
      3. Thermocouple has burned out.
   B. Corrective actions (where applicable):
      1. Decrease fuel feed rate.
      2. Reduce sludge feed rate.
      3. Increase air feed rate.
      4. Replace thermocouple.
2. Furnace temperature is too low.
   A. Causal factors:
      1. Moisture content of the sludge has increased.
      2. Fuel system malfunction.
      3. Excessive air feed rate.
      4. Flame is out.
   B. Corrective actions (where applicable):
      1. Increase fuel feed rate until dewatering operation improves.
      2. Establish proper fuel feed rate.
      3. Decrease air feed rate.
      4. Increase sludge feed rate.
      5. Relight furnace.
3. Oxygen content of stack gas is too high.
   A. Causal factors:
      1. Sludge feed rate is too low.
      2. Sludge feed system blockage.
      3. Air feed rate is too high.
   B. Corrective actions (where applicable):
      1. Increase sludge feed rate.
      2. Clear any feed system blockages.
      3. Decrease air feed rate.
4. Oxygen content of stack gas is too low.
   A. Causal factors:
      1. Volatile or grease content of the sludge has increased.
      2. Air feed rate is too low.
   B. Corrective actions (where applicable):
      1. Increase air feed rate.
      2. Decrease sludge feed rate.
      3. Increase air feed rate.
5. Furnace refractories have deteriorated.
   A. Causal factor:
      1. Rapid start-up or shutdown of furnace.
   B. Corrective actions:
      1. Repair furnace refractories.
      2. Follow specified start-up or shutdown procedures.
6. Unusually high cooling effect.
   A. Causal factor:
      1. Air leak.
   B. Corrective action:
      1. Locate and repair leak.
7. Short hearth life.
   A. Causal factor:
      1. Uneven firing.
   B. Corrective action:
      1. Fire hearths equally on both sides.
8. Center shaft shear pin failure.
   A. Causal factors:
      1. Rabble arm is dragging on hearth.
      2. Debris is caught under the arm.
   B. Corrective actions (where applicable):

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1. Adjust rabble arm to eliminate rubbing.
2. Remove debris.

9. Scrubber temperature is too high.
   A. Causal factor:
      1. Low water flow to scrubber.
   B. Corrective action:
      1. Adjust water flow to proper level.
10. Stack gas temperatures are too low.
   A. Causal factors:
      1. Inadequate fuel feed supply.
      2. Excessive sludge feed rate.
   B. Corrective actions (where applicable):
      1. Increase fuel feed rate.
      2. Decrease sludge feed rate.
11. Stack gas temperatures are too high.
   A. Causal factors:
      1. Sludge has higher volatile content (heat value).
      2. Excessive fuel feed rate.
   B. Corrective actions (where applicable):
      1. Increase air feed rate.
      2. Decrease sludge feed rate.
      3. Decrease fuel feed rate.
12. Furnace burners are slagging up.
   A. Causal factor:
      1. Burner design.
   B. Corrective action:
      1. Replace burners with newer designs that reduce slagging.
13. Rabble arms are dropping.
   A. Causal factors:
      1. Excessive hearth temperatures.
      2. Loss of cooling air.
   B. Corrective actions (where applicable):
      1. Maintain temperatures within proper range.
      2. Discontinue injection of scum into the hearth.
      3. Repair cooling air system immediately.
14. Excessive air pollutants are in stack gas.
   A. Causal factors:
      1. Incomplete combustion (insufficient air).
      2. Air pollution control malfunction.
   B. Corrective actions (where applicable):
      1. Raise air-fuel ratio.
      2. Repair or replace broken equipment.
15. Flashing or explosions.
   A. Causal factor:
      1. Scum or grease additions.
   B. Corrective action:
      1. Remove scum or grease before incineration.

Fluidized Beds

1. Bed temperature is falling.
   A. Causal factors:
      1. Inadequate fuel supply.
      2. Excessive sludge feed rate.
      3. Excessive sludge moisture levels.
      4. Excessive air flow.
   B. Corrective actions (where applicable):
      1. Increase fuel supply.
      2. Repair fuel system malfunction.
      3. Decrease sludge feed rate.
      4. Correct sludge de-watering process problem.
      5. Decrease airflow rate.
2. Low (<3%) oxygen in exhaust gas.
   A. Causal Factors:
      1. Low air flow rate.
      2. Fuel feed rate is too high.
   B. Corrective actions (where applicable):
      1. Increase blower air feed rate.
      2. Reduce fuel feed rate.
3. Excessive (>6%) oxygen in exhaust gas.
   A. Causal factor:
      1. Sludge feed rate is too low.
   B. Corrective actions (where applicable):
      1. Increase sludge feed rate.
      2. Adjust fuel feed rate to maintain steady bed temperature.
4. Erratic bed depth on control panel.
   A. Causal factor:
      1. Bed pressure taps are plugged with solids.
   B. Corrective actions (where applicable):
      1. Tap a metal rod into pressure tap pipe when the unit is not in operation.
      2. Apply compressed air to pressure tap while the unit is in operation (follow manufacturer's safety guidelines).
5. Preheat burner fails and alarm sounds.
   A. Causal factors:
      1. Pilot flame is not receiving fuel.
      2. Pilot flame is not receiving spark.
      3. Defective pressure regulators.
      4. Pilot flame ignites, but flame scanner malfunctions.
   B. Corrective actions (where applicable):
      1. Correct fuel system problem.
      2. Replace defective part.
      3. Replace defective regulators.
      4. Clear scanner sight glass.
      5. Replace defective scanner.
6. Bed temperature is too high.
   A. Causal factors:

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1. Bed gun fuel feed rate is too high.
2. Grease or high organic content in sludge (high heat value).

B. Corrective Actions (where applicable):
1. Reduce bed gun fuel feed rate.
2. Increase airflow rate.
3. Decrease sludge fuel rate.

7. Bed temperature reads off scale.
   A. Causal factor:
      1. Thermocouple has burned out.
   B. Corrective action:
      1. Replace thermocouple.
8. Scrubber inlet shows high temperature.
   A. Causal factors:
      1. No water flowing in scrubber.
      2. Spray nozzles are plugged.
      3. Ash water not recirculating.
   B. Corrective actions (where applicable):
      1. Open valves to provide water.
      2. Correct system malfunction to provide required pressure.
      3. Clear nozzles and strainers.
      4. Repair or replace recirculation pump.
      5. Unclog scrubber discharge line.
9. Poor bed fluidization.
   A. Causal factor:
      1. Sand leakage through support plate during shutdown.
   B. Corrective actions (where applicable):
      1. Clear wind box.
      2. Clean wind box at least once per month.

18.13.4.6 Land Application of Biosolids

The purpose of land application of biosolids is to dispose of the treated biosolids in an environmentally sound manner by recycling nutrients and soil conditioners. In order to be land applied, wastewater biosolids must comply with state and federal biosolids management and disposal regulations. Biosolids must not contain materials that are dangerous to human health (i.e., toxicity, pathogenic organisms, etc.) or dangerous to the environment (i.e., toxicity, pesticides, heavy metals, etc.).

Treated biosolids are land applied by either direct injection or application and plowing in (incorporation).

18.13.4.6.1 Process Control: Sampling and Testing

Land application of biosolids requires precise control to avoid problems. The quantity and the quality of biosolids applied must be accurately determined. For this reason, the operator's process control activities include biosolids sampling and testing functions.

Biosolids sampling and testing includes determination of percent solids, heavy metals, organic pesticides and herbicide, alkalinity, total organic carbon, organic nitrogen, and ammonia nitrogen.

18.13.4.6.2 Process Control Calculations

Process control calculations include determining disposal cost, plant available nitrogen (PAN), application rate (dry tons and wet tons per acre), metals loading rates, maximum allowable applications based upon metals loading, and site life based on metals loading.

18.13.4.6.2.1 Disposal Cost

The cost of disposal of biosolids can be determined by the following equation:

$$\text{Cost} = \text{Wet Tons Biosolids Produced/Year} \times \text{\% Solids} \times \text{Cost/Dry Ton} \tag{18.81}$$

Example 18.88

Problem:

The treatment system produces 1925 wet tons of biosolids for disposal each year. The biosolids are 18% solids. A contractor disposes of the biosolids for $28.00 per dry ton. What is the annual cost for sludge disposal?

Solution:

$$\text{Cost} = 1925 \text{ wet tons/year} \times 0.18 \times \$28.00\text{/dry ton}$$

$$= \$9702$$

18.13.4.6.2.2 Plant Available Nitrogen

One factor considered when land applying biosolids is the amount of nitrogen in the biosolids available to the plants grown on the site. This includes ammonia nitrogen and organic nitrogen. The organic nitrogen must be mineralized for plant consumption. Only a portion of the organic nitrogen is mineralized per year. The mineralization factor (f1) is assumed to be 0.20. The amount of ammonia nitrogen available is directly related to the time elapsed between applying the biosolids and incorporating (plowing) the sludge into the soil. We provide volatilization rates based upon this example below:

$$\text{PAN (lb/dry ton)} = \left[\left(\text{Organic Nitrogen (mg/kg)} \times f_1\right) + \left(\text{Ammonia Nitrogen (mg/kg)} \times V_1\right)\right] \times 0.002 \text{ lb/dry ton} \tag{18.82}$$

where

f_1 = Mineral rate for organic nitrogen (assume 0.20)

V_1 = Volatilization rate ammonia nitrogen

V_1 = 1.00 if biosolids are injected

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$V_1 = 0.85$ if biosolids are plowed in within 24 h
$V_1 = 0.70$ if biosolids are plowed in within 7 d

EXAMPLE 18.89

Problem:

The biosolids contain 21,000 mg/kg of organic nitrogen and 10,500 mg/kg of ammonia nitrogen. The biosolids are incorporated into the soil within 24 h after application. What is the PAN per dry ton of solids?

Solution:

$$\text{PAN (lb/dry ton)}$$
$$= [(21{,}000 \text{ mg/kg} \times 0.20) + (10{,}500 \times 0.85)] \times 0.002$$
$$= 26.3 \text{ lb PAN/dry ton}$$

18.13.4.6.2.3 Application Rate Based on Crop Nitrogen Requirement

In most cases, the application rate of domestic biosolids to crop lands will be controlled by the amount of nitrogen the crop requires. The biosolids application rate based upon the nitrogen requirement is determined by the following:

1. Using an agriculture handbook to determine the nitrogen requirement of the crop to be grown
2. Determining the amount of sludge in dry tons required to provide this much nitrogen

$$\text{Dry tons/acre} = \frac{\text{Plant Nitrogen Requirement (lb/acre)}}{\text{PAN (lb/dry ton)}} \quad (18.83)$$

EXAMPLE 18.90

Problem:

The crop to be planted on the land application site requires 150 lb of nitrogen per acre. What is the required biosolids application rate if the PAN of the biosolids is 30 lb/dry ton?

Solution:

$$\text{Dry tons/acre} = \frac{150 \text{ lb nitrogen/acre}}{30 \text{ lb/dry ton}} \quad (18.84)$$
$$= 5 \text{ dry tons/acre}$$

18.13.4.6.2.4 Metals Loading

When biosolids are land applied, metals concentrations are closely monitored and their loading on land application sites are calculated:

$$\text{Loading Rate (lb/acre)} = \text{Metal Concentration (mg/kg)} \times 0.002 \text{ lb/dry ton} \times \text{Applied Rate (dry tons/acre)} \quad (18.85)$$

EXAMPLE 18.91

Problem:

The biosolids contain 14 mg/kg of lead. Biosolids are currently being applied to the site at a rate of 11 dry tons/acre. What is the metals loading rate for lead in pounds per acre?

Solution:

$$\text{Loading Rate (lb/acre)}$$
$$= 14 \text{ mg/kg} \times 0.002 \text{ lb/dry ton} \times 11 \text{ dry tons}$$
$$= 0.31 \text{ lb/acre}$$

18.13.4.6.2.5 Maximum Allowable Applications Based upon Metals Loading

If metals are present, they may limit the total number of applications a site can receive. Metals loading are normally expressed in terms of the maximum total amount of metal that can be applied to a site during its use:

$$\text{Applications} = \frac{\text{Maximum Allowable Cumulative Load for the Metal (lb/acre)}}{\text{Metal Loading (lb/acre/application)}} \quad (18.86)$$

EXAMPLE 18.92

Problem:

The maximum allowable cumulative lead loading is 48.0 lb/acre. Based upon the current loading of 0.35 lb/acre, how many applications of biosolids can be made to this site?

Solution:

$$\text{Applications} = \frac{48 \text{ lb/acre}}{0.35 \text{ lb/acre/application}}$$
$$= 137 \text{ applications}$$

18.13.4.6.2.6 Site Life Based on Metals Loading

The maximum number of applications based upon metals loading and the number of applications per year can be used to determine the maximum site life:

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$$\text{Site Life (years)} = \frac{\text{Maximum Allowable Applications}}{\text{Number of Applications Planned/Year}} \quad (18.87)$$

Example 18.93

Problem:

Biosolids is currently applied to a site twice annually. Based upon the lead content of the biosolids, the maximum number of applications is determined to be 135 applications. Based upon the lead loading and the application rate, how many years can this site be used?

Solution:

$$\text{Site Life (years)} = \frac{135 \text{ applications}}{2 \text{ applications/year}} = 68 \text{ years}$$

Note: When more than one metal is present, the calculations must be performed for each metal. The site life would then be the lowest value generated by these calculations.

18.14 PERMITS, RECORDS, AND REPORTS

Permits, records, and reports play a significant role in wastewater treatment operations. In fact, in regards to the permit, one of the first things any new operator quickly learns is the importance of "making permit" each month. In this section, we briefly cover National Pollutant Discharge Elimination System (NPDES) permits and other pertinent records and reports the wastewater operator must be familiar with.

Note: The discussion that follows is general in nature; it does not necessarily apply to any state in particular, but instead is an overview of permits, records, and reports that are an important part of wastewater treatment plant operations. For specific guidance on requirements for your locality, refer to your state water control board or other authorized state agency for information. In this handbook, the term board signifies the state-reporting agency.

18.14.1 Definitions

There are several definitions that should be discussed prior to discussing the permit requirements for records and reporting:

Average daily limitation the highest allowable average over a 24-h period, calculated by adding all of the values measured during the period and dividing the sum by the number of values determined during the period.

Average hourly limitation the highest allowable average for a 60-min period, calculated by adding all of the values measured during the period and dividing the sum by the number of values determined during the period.

Average monthly limitation the highest allowable average over a calendar month, calculated by adding all of the daily values measured during the month and dividing the sum by number of daily values measured during the month.

Average weekly limitation the highest allowable average over a calendar week, calculated by adding all of the daily values measured during the calendar week and dividing the sum by the number of daily values determined during the week.

Daily discharge the discharge of a pollutant measured during a calendar day or any 24-h period that reasonably represents the calendar for the purpose of sampling. For pollutants with limitations expressed in units of weight, the daily discharge is calculated as the total mass of the pollutant discharged over the day. For pollutants with limitations expressed in other units, the daily discharge is calculated as the average measurement of the pollutant over the day.

Discharge monitoring report forms used in the reporting of self-monitoring results of the permittee.

Discharge permit State Pollutant Discharge Elimination System (state-PDES) permit that specifies the terms and conditions under which a point source discharge to state waters is permitted.

Effluent limitation any restriction by the state board on quantities, discharge rates, or concentrations of pollutants that are discharged from point sources into state waters.

Maximum daily discharge the highest allowable value for a daily discharge.

Maximum discharge the highest allowable value for any single measurement.

Minimum discharge the lowest allowable value for any single measurement.

Point source any discernible, defined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, vessel, or other floating craft, from which pollutants are or may be discharged. This definition does not include return flows from irrigated agricultural land.

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18.14.2 NPDES Permits

In the U.S., all treatment facilities that discharge to state waters must have a discharge permit issued by the state water control board or other appropriate state agency. This permit is known on the national level as the National NPDES permit and on the state level as the state-PDES permit. The permit states the specific conditions that must be met to legally discharge treated wastewater to state waters. The permit contains general requirements (applying to every discharger) and specific requirements (applying only to the point source specified in the permit).

A general permit is a discharge permit that covers a specified class of dischargers. It is developed to allow dischargers with the specified category to discharge under specified conditions.

All discharge permits contain general conditions. These conditions are standard for all dischargers and cover a broad series of requirements. Read the general conditions of the treatment facility's permit carefully.

Permittees must retain certain records. These records include:

Monitoring:

1. Date, time, and exact place of sampling or measurements
2. Names of the individuals performing sampling or measurement
3. Dates and times analyses were performed
4. Names of the individuals who performed the analyses
5. Analytical techniques or methods used
6. Observations, readings, calculations, bench data, and results
7. Instrument calibration and maintenance
8. Original strip chart recordings for continuous monitoring
9. Information used to develop reports required by the permit
10. Data used to complete the permit application

Note: All records must be kept at least 3 years (longer at the request of the state board).

18.14.2.1 Reporting

In general, reporting must be made under the following conditions and situations (requirements may vary depending upon state regulatory body with reporting authority):

1. Unusual or extraordinary discharge reports — The board must be notified by telephone within 24 h of occurrence and submit written report within 5 d. The report must include:
   A. Description of the non-compliance and its cause.
   B. Noncompliance dates, times, and duration.
   C. Steps planned or taken to reduce or eliminate occurrence.
   D. Steps planned or taken to prevent reoccurrence.
2. Anticipated noncompliance — The board must be notified at least 10 d in advance of any changes to the facility or activity that may result in noncompliance.
3. Compliance schedules — Compliance or noncompliance with any requirements contained in compliance schedules must be reported no later than 14 d following scheduled date for completion of the requirement.
4. 24-h Reporting — Any noncompliance that may adversely affect state waters or may endanger public health must be reported orally with 24 h of the time the permittee becomes aware of the condition. A written report must be submitted within 5 d.
5. Discharge monitoring reports (DMRs) — These reports consist of self-monitoring data generated during a specified period (normally 1 month). When completing the DMR, remember:
   A. More frequent monitoring must be reported.
   B. All results must be used to complete reported values.
   C. Pollutants monitored by an approved method, but not required by the permit must be reported.
   D. No empty blocks on the form should be left blank.
   E. Averages are arithmetic unless noted otherwise.
   F. Appropriate significant figures should be used.
   G. All bypasses and overflows must be reported.
   H. The licensed operator must sign the report.
   I. Responsible official must sign the report.
   J. Department must receive by the 10th of the following month.

18.14.2.2 Sampling and Testing

The general requirements of the permit specify minimum sampling and testing that must be performed on the plant discharge. The permit will also specify the frequency of sampling, sample type, and length of time for composite samples.

Unless a specific method is required by the permit, all sample preservation and analysis must be in compliance

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with the requirements set forth in the Code of Federal Regulations, *Guidelines Establishing Test Procedures for the Analysis of Pollutants Under the Clean Water Act* (40 CFR 136).

Note: All samples and measurements must be representative of the nature and quantity of the discharge.

18.14.2.3 Effluent Limitations

The permit sets numerical limitations on specific parameters contained in the plant discharge. Limits may be expressed as:

1. Average monthly quantity (kg/d)
2. Average monthly concentration (mg/L)
3. Average weekly quantity (kg/d)
4. Average weekly concentration (mg/L)
5. Daily quantity (kg/d)
6. Daily concentration (mg/L)
7. Hourly average concentration (mg/L)
8. Instantaneous minimum concentration (mg/L)
9. Instantaneous maximum concentration (mg/L)

18.14.2.4 Compliance Schedules

The facility may require additional construction or other modifications to fully comply with the final effluent limitations. If this is the case, the permit will contain a schedule of events to be completed to achieve full compliance.

18.14.2.5 Special Conditions

Any special requirements or conditions set for approval of the discharge will be contained in this section. Special conditions may include:

1. Monitoring required to determine effluent toxicity
2. Pretreatment program requirements

18.14.2.6 Licensed Operator Requirements

The permit will specify, based on the treatment system complexity and the volume of flow treated, the minimum license classification required to be the designated responsible charge operator.

18.14.2.7 Chlorination or Dechlorination Reporting

Several reporting systems apply to chlorination or chlorination followed by dechlorination. It is best to review this section of the specific permit for guidance. Contact the appropriate state regulatory agency for any needed clarification.

18.14.2.8 Reporting Calculations

Failure to accurately calculate report data will result in violations of the permit. The basic calculations associated with completing the DMR are covered below.

18.14.2.8.1 Average Monthly Concentration

The average monthly concentration (AMC) is the average of the results of all tests performed during the month:

$$\text{AMC}\ (\text{mg/L}) = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{N}} \tag{18.88}$$

where N = tests during a month.

18.14.2.8.2 Average Weekly Concentration (AWC)

The average weekly concentration (AWC) is the results of all the tests performed during a calendar week. A calendar week must start on Sunday and end on Saturday and be completely within the reporting month. A weekly average is not computed for any week that does not meet these criteria:

$$\text{AWC}\ (\text{mg/L}) = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{N}} \tag{18.89}$$

where N = tests during a calendar week.

18.14.2.8.3 Average Hourly Concentration

The average hourly concentration (AHC) is the average of all test results collected during a 60-min period:

$$\text{AHC}\ (\text{mg/L}) = \frac{\sum \text{Test}_1 + \text{Test}_2 + \text{Test}_3 + \ldots + \text{Test}_n}{\text{N}} \tag{18.90}$$

where N = tests during a 60-min period.

18.14.2.8.4 Daily Quantity

Daily quantity (DQ) is the quantity of a pollutant in kilograms per day discharged during a 24-h period:

$$\text{DQ}\ (\text{kg/d}) = \text{Concentration}\ (\text{mg/L}) \times \text{Q}\ (\text{MGD}) \times 3.785\ \text{kg/MG/mg/L} \tag{18.91}$$

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18.14.2.8.5 Average Monthly Quantity

Average monthly quantity (AMQ) is the average of all the individual daily quantities determined during the month:

$$\text{AMQ}\ (\text{kg/d}) = \frac{\sum DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{N} \tag{18.92}$$

where N = tests during a month.

18.14.2.8.6 Average Weekly Quantity

The average weekly quantity (AWQ) is the average of all the daily quantities determined during a calendar week. A calendar week must start on Sunday and end on Saturday and be completely within the reporting month. A weekly average is not computed for any week that does not meet these criteria:

$$\text{AWQ}\ (\text{kg/d}) = \frac{\sum DQ_1 + DQ_2 + DQ_3 + \ldots + DQ_n}{N} \tag{18.93}$$

where N = tests during a calendar week.

18.14.2.8.7 Minimum Concentration

The minimum concentration is the lowest instantaneous value recorded during the reporting period.

18.14.2.8.8 Maximum Concentration

Maximum concentration is the highest instantaneous value recorded during the reporting period.

18.14.2.8.9 Bacteriological Reporting

Bacteriological reporting is used for reporting fecal coliform test results. To make this calculation the geometric mean calculation is used and all monthly geometric means are computed using all the test values. Note that weekly geometric means are computed using the same selection criteria discussed for average weekly concentration and quantity calculations. The easiest method used in making this calculation requires a calculator, which can perform logarithmic (log) or Nth root functions:

$$\text{Geometric Mean} = \frac{\log X_1 + \log X_2 + \log X_3 + \ldots + \log X_n}{N} \tag{18.94}$$

where N = number of tests.
or

$$\text{Geometric Mean} = \sqrt[n]{X_1 + X_2 + \ldots + X_n}$$

18.15 CHAPTER REVIEW QUESTIONS AND PROBLEMS

18.1. Who must sign the DMR?
18.2. What does the COD test measure?
18.3. Give three reasons for treating wastewater.
18.4. Name two types of solids based on physical characteristics.
18.5. Define organic and inorganic.
18.6. Name four types of microorganisms that may be present in wastewater.
18.7. When organic matter is decomposed aerobically, what materials are produced?
18.8. Name three materials or pollutants, which are not removed by the natural purification process.
18.9. What are the used water and solids from a community that flow to a treatment plant called?
18.10. Where do disease-causing bacteria in wastewater originate?
18.11. What does the term pathogenic mean?
18.12. What is wastewater called that comes from the household?
18.13. What is wastewater called that comes from industrial complexes?
18.14. The lab test indicates that a 500-g sample of sludge contains 22 g of solids. What are the percent solids in the sludge sample?
18.15. The depth of water in the grit channel is 28 in. What is the depth in feet?
18.16. The operator withdraws 5250 gal of solids from the digester. How many pounds of solids have been removed?
18.17. Sludge added to the digester causes a 1920–ft^3 change in the volume of sludge in the digester. How many gallons of sludge have been added?
18.18. The plant effluent contains 30 mg/L solids. The effluent flow rate is 3.4 MGD. How many pounds per day of solids are discharged?
18.19. The plant effluent contains 25 mg/L BOD. The effluent flowrate is 7.25 MGD. How many kilograms per day of BOD are being discharged?
18.20. The operator wishes to remove 3280 lb/d of solids from the activated sludge process. The waste activated sludge concentration is 3250 mg/L. What is the required flow rate in million gallons per day?
18.21. The plant influent includes an industrial flow that contains 240 mg/L BOD. The industrial flow is 0.72 MGD. What is the population equivalent for the industrial contribution in people per day?

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18.22. The label of hypochlorite solution states that the specific gravity of the solution is 1.1288. What is the weight of 1 gal of the hypochlorite solution?

18.23. What must be done to the cutters in a comminutor to ensure proper operation?

18.24. What is grit? Give three examples of material which is considered to be grit.

18.25. The plant has three channels in service. Each channel is 2 ft wide and has a water depth of 3 ft. What is the velocity in the channel when the flow rate is 8 MGD?

18.26. The grit from the aerated grit channel has a strong hydrogen sulfide odor upon standing in a storage container. What does this indicate and what action should be taken to correct the problem?

18.27. What is the purpose of primary treatment?

18.28. What is the purpose of the settling tank in the secondary or biological treatment process?

18.29. The circular settling tank is 90 ft in diameter and has a depth of 12 ft. The effluent weir extends around the circumference of the tank. The flow rate 2.25 MGD. What is the detention time in hours, surface loading rate in gallons per day per square foot and weir overflow rate in gallons per day per foot?

18.30. Give three classifications of ponds based upon their location in the treatment system.

18.31. Describe the processes occurring in a raw sewage stabilization pond (facultative).

18.32. How do changes in the season affect the quality of the discharge from a stabilization pond?

18.33. What is the advantage of using mechanical or diffused aeration equipment to provide oxygen?

18.34. Name three classifications of trickling filters. Identify the classification that produces the highest quality effluent.

18.35. Microscopic examination reveals a predominance of rotifers. What process adjustment does this indicate is required?

18.36. Increasing the wasting rate will _____ the MLSS, _____ the return concentration, _____ the MCRT, _____ the F:M ratio, and _____ the SVI.

18.37. The plant currently uses 45.8 lb of chlorine per day. Assuming the chlorine usage will increase by 10% during the next year, how many 2000-lb cylinders of chlorine will be needed for the year (365 days)?

18.38. The plant has 6 2000-lb cylinders on hand. The current dose of chlorine being used to disinfect the effluent is 6.2 mg/L. The average effluent flow rate is 2.25 MGD. Allowing 15 days for ordering and shipment, when should the next order for chlorine be made?

18.39. The plant feeds 38 lb of chlorine per day and uses 150-lb cylinders. Chlorine use is expected to increase by 11% next year. The chlorine supplier has stated that the current price of chlorine ($0.170/lb) will increase by 7.5% next year. How much money should the town budget for chlorine purchases for the next year (365 days)?

18.40. The sludge pump operates 30 min every 3 h. The pump delivers 70 gal/min. If the sludge is 5.1% solids and has a volatile matter content of 66%, how many pounds of volatile solids are removed from the settling tank each day?

18.41. The aerobic digester has a volume of 63,000 gal. The laboratory test indicates that 41 mg of lime were required to increase the pH of a 1-L sample of digesting sludge from 6 to the desired 7.1. How many pounds of lime must be added to the digester to increase the pH of the unit to 7.4?

18.42. The digester has a volume of 73,500 gal. Sludge is added to the digester at the rate of 2750 gal/d. What is the SRT in days?

18.43. The raw sludge pumped to the digester contains 72% volatile matter. The digested sludge removed from the digester contains 48% volatile matter. What is the percent volatile matter reduction?

18.44. The acronym NPDES stands for _____.

18.45. How can primary sludge be freshened going into a gravity thickener?

18.46. A neutral solution has a pH value of _____.

18.47. Why is the seeded BOD test required for some samples?

18.48. What is the foremost advantage of the COD over the BOD?

18.49. High mixed liquor concentration is indicated by a _____ aeration tank foam.

18.50. What typically happens to the activity level of bacteria when the temperature is increased?

18.51. List three factors other than food that affects the growth characteristics of activated sludge.

18.52. What are the characteristics of facultative organisms?

18.53. BOD measures the amount of _____ material in wastewater.

18.54. The activated sludge process requires _____ in the aeration tank to be successful.

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18.55. The activated sludge process can not be successfully operated with a _____ clarifier.
18.56. The activated biosolids process can successfully remove _____ BOD.
18.57. Successful operation of a complete mix reactor in the endogenous growth phase is _____.
18.58. The bacteria in the activated biosolids process are either _____ or _____.
18.59. Step feed activated biosolids processes have _____ mixed liquor concentrations in different parts of the tank.
18.60. An advantage of contact stabilization compared to complete mix is _____ aeration tank volume.
18.61. Increasing the _____ of wastewater increases the BOD in the activated biosolids process.
18.62. Bacteria need phosphorus to successfully remove _____ in the activated biosolids process.
18.63. The growth rate of microorganisms is controlled by the _____ ratio.
18.64. Adding chlorine just before the _____ can control alga growth.
18.65. What is the purpose of the secondary clarifier in an activated biosolids process?
18.66. The _____ growth phase should occur in a complete mix activated biosolids process.
18.67. The typical DO value for activated biosolids plants is between _____ and _____ mg/L.
18.68. In the activated biosolids process, what change would an operator normally expect to make when the temperature decreases from 25°C to15°C?
18.69. In the activated biosolids process, what change must be made to increase the MLVSS?
18.70. In the activated biosolids process, what change must be made to increase the F:M?
18.71. What does the Gould sludge age assume to be the source of the MLVSS in the aeration tank?
18.72. What is one advantage of complete mix over plug flow?
18.73. The grit in the primary sludge is causing excessive wear on primary treatment sludge pumps. The plant uses an aerated grit channel. What action should be taken to correct this problem?
18.74. When the MCRT increases, the MLSS concentration in the aeration tank _____.
18.75. Exhaust air from a chlorine room should be taken from where?
18.76. If chlorine costs $0.21/lb, what is the daily cost to chlorinate a 5-MGD flow rate at chlorine feed rate of 2.6 mg/L?
18.77. What is the term that describes a normally aerobic system from which the oxygen has temporarily been depleted?
18.78. The ratio that describes the minimum amount of nutrients theoretically required for an activated sludge system is 100:5:1. What are the elements that fit this ratio?
18.79. A flotation thickener is best used for what type of sludge?
18.80. True of false: Drying beds are an example of a sludge stabilization process.
18.81. The minimum flow velocity in collection systems should be _____.
18.82. What effect will the addition of chlorine, acid, alum, carbon dioxide, or sulfuric acid have on the pH of wastewater?
18.83. An amperometric titrater is used to measure _____.
18.84. The normal design detention time for primary clarifier is _____.
18.85. The volatile acids-alkalinity ratio in an anaerobic digester should be approximately _____.
18.86. The surface loading rate in a final clarifier should be approximately _____.
18.87. In a conventional effluent chlorination system the chlorine residual measured is mostly in the form of _____.
18.88. For a conventional activated biosolids process, the Food:Microorganism (F:M) ratio should be in the range of ___ to ____.
18.89. Denitrification in a final clarifier can cause clumps of sludge to rise to the surface. The sludge flocs attach to small sticky bubbles of _____ gas.
18.90. An anaerobic digester is covered and kept under positive pressure to do what?
18.91. During the summer months, the major source of oxygen added to a stabilization pond is _____.
18.92. Which solids cannot be removed by vacuum filtration?
18.93. The odor recognition threshold for H_2S is reported to be as low as:

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Appendix A

Answers to Chapter Review Questions and Problems

CHAPTER 1

1.1. A pattern or point of view that determines what is seen as reality.
1.2. A change in the way things are understood and done.
1.3. The five elements of the multiple-barrier approach are:
   a. Assessing and protecting drinking water sources
   b. Optimizing treatment processes
   c. Ensuring the integrity of distribution systems
   d. Effecting correct cross-connection control procedures
   e. Continuous monitoring and testing of the water before it reaches the tap
1.4. Water and wastewater operations are usually low-profile activities and much of water and wastewater infrastructure is buried underground.
1.5. Secondary
1.6. Privatization means allowing private enterprise to compete with government in providing public services, such as water and wastewater operations. Reengineering is the systematic transformation of an existing system into a new form to realize quality improvements in operation, systems capability, functionality, and performance at lower cost, schedule, or risk to the customer.
1.7. A process for rigorously measuring your performance vs. best-in-class operations, and using the analysis to meet and exceed the best in class.
1.8. Planning, research, observation, analysis, adaptation

CHAPTER 2

2.1. Operators are exposed to the full range of hazards and work under all weather conditions.
2.2. Plants are upgrading to computerized operations.
2.3. Computerized maintenance management system
2.4. HAZMAT emergency response technician 24-hour certification
2.5. Safe Drinking Water Act

CHAPTER 3

3.1. Matching answers:

1.	o	14.	v
2.	c	15.	r
3.	t	16.	w
4.	j	17.	l
5.	s	18.	x
6.	p	19.	m
7.	d	20.	y
8.	I	21.	f
9.	e	22.	b
10.	q	23.	z
11.	u	24.	h
12.	k	25.	n
13.	a	26.	g

CHAPTER 4

4.1. Whole
4.2. 9/16 = 1.5 (mean)
4.3. 13
4.4. 6/9
4.5. 5/8
4.6. 9/14
4.7. 5/8

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4.8. 0.75
4.9. 1×10^7
4.10. 270 ft^2
4.11. 12,000 ft^2
4.12. 624 gal/hr
4.13. 235.5 ft^3
4.14. 17.3 psi
4.15. Base
4.16. Radius
4.17. Circumference, perimeter
4.18. The word of means to multiply, and means to add, per means to divide and less means to subtract
4.19. When no grouping is given problems are worked in the following order: first, multiplication and division in the order written and then addition and subtraction
4.20. 4916 lb
4.21. 0.218 MGD
4.22. 10,597 people
4.23. 290 mg/L BOD
4.24. 9.46 lb/gal
4.25. 106 d
4.26. 33,360 lb
4.27. 91%
4.28. 11,176 people
4.29. 9.5 4 lb
4.30. 2.52 MGD
4.31. 181 gal/min
4.32. 5.9 mg/L
4.33. 500 gal
4.34. 44.8 d
4.35. 490.9 ft^2
4.36. 71,957.8 gal
4.37. 19.2 min
4.38. 21,605.4 in^3
4.39. 24,220 gal
4.40. 21.7 psi
4.41. 672 gal/min
4.42. Q = 0.18 ft^3/sec
4.43. 41 min
4.44. 0.5 h
4.45. 4.2 h
4.46. 2.9 MGD
4.47. 13.6 hp
4.48. 45,453 lb
4.49. 50 Bhp
4.50. 1,233 lb/d
4.51. 9.62 lb/gal

CHAPTER 5

5.1. 1.26 ft
5.2. 0.77 ft
5.3. Eccentric, segmental
5.4. Flow nozzle
5.5. Ultrasonic flowmeter
5.6. 4937 gal
5.7. 4.57
5.8. 213,904 ft^3
5.9. 103 ft
5.10. 8064 lb
5.11. Always constant
5.12. Pressure head is pressure due to the depth of water.
5.13. A hydraulic grade line is the line that connects the piezometric surface along a pipeline.
5.14. 0.28 ft
5.15. 254.1 ft
5.16. 6.2×10^{-8}
5.17. 0.86 ft
5.18. Velocity head is the pressure energy due to the velocity of the water.
5.19. Suction lift is a pumping condition where the size of the impeller of the pump and above the surface of the water from which the pump is running.
5.20. Energy grade line is the slope of the specific energy line.

CHAPTER 6

6.1. Alternator
6.2. Electromagnetic induction is the effect that causes current flow in a conductor moving across magnetic lines of force.
6.3. Mechanical; electrical
6.4. Increases; decreases; decreases; increases
6.5. The purpose of a fuse is to protect an electrical circuit and load
6.6. 0.2 Ω
6.7. Orbits; shells
6.8. Protons; neutrons
6.9. The value of the resistor, the length of the conductors, and the diameter of the conductors
6.10. Direct current flow does not change direction, while AC current periodically changes direction
6.11. The magnetic poles
6.12. The flux lines, or magnetic flux, along which a magnetic force acts
6.13. Natural magnet, permanent magnets, and electromagnets
6.14. Chemistry
6.15. Battery; two
6.16. A series circuit has only one path for current flow, while a parallel circuit has more than one path.
6.17. Source voltage
6.18. Voltage drop

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6.19. Counterclockwise
6.20. 2 A
6.21. 12 V
6.22. 16 W
6.23. 80 W
6.24. Less; more
6.25. Resistivity
6.26. Circular mil
6.27. Circular mil
6.28. Conductivity
6.29. Smaller
6.30. Doubles
6.31. It will withstand high voltages.
6.32. Flux density and magnetic field strength are directly proportional. As flux density increases, magnetic field strength also increases.
6.33. The type of material and the flux density
6.34. North pole
6.35. The frequency of the voltage will increase.
6.36. 141.4 V
6.37. A voltage is induced in the conductor
6.38. AC: cut; counter
6.39. Counter
6.40. Current has an associated magnetic field
6.41. Increase
6.42. Increase

CHAPTER 7

7.1. Positive-displacement
7.2. High-viscosity
7.3. Positive-displacement
7.4. High
7.5. High
7.6. Eye
7.7. Static; dynamic
7.8. Shut off
7.9. $V^2/2g$
7.10. Total head
7.11. Head capacity, efficiency, horsepower demand
7.12. Water
7.13. Suction lift
7.14. Elevation head
7.15. Water hp; pump efficiency
7.16. Centrifugal force
7.17. Stuffing box
7.18. Impeller
7.19. Rings; impeller
7.20. Casing
7.21. The function of the pump's impeller is to supply energy to the water (fluid).
7.22. Close-coupled
7.23. Radially
7.24. Open, semi-open, closed
7.25. Double volute
7.26. Cap; slides
7.27. Wearing rings
7.28. Matching answers:
   a. 8
   b. 7
   c. 4
   d. 1
   e. 5
   f. 2
   g. 3
   h. 10
   i. 6
   j. 9

CHAPTER 8

8.1. An expansion joint is a flexible piping component that absorbs thermal and terminal movement.
8.2. Fluid
8.3. Fluid
8.4. Connected
8.5. Flow
8.6. Pressure loss
8.7. Increases
8.8. Automatically
8.9. Insulation
8.10. Leakage
8.11. Quadrupled
8.12. Routine preventive maintenance
8.13. 12
8.14. Schedule; thickness
8.15. Increases
8.16. Ferrous
8.17. Increases
8.18. Iron oxide is another name for rust.
8.19. Cast-iron
8.20. Iron
8.21. Corrosion
8.22. Decreases
8.23. Clay, concrete, plastic, glass, or wood
8.24. Corrosion-proof
8.25. Cement
8.26. Pressed
8.27. Turbulent; lower
8.28. Steel
8.29. Fusion
8.30. Flexible
8.31. Aluminum
8.32. Annealed
8.33. Fusion
8.34. Metals; plastics
8.35. Laminar

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8.36. Reinforced nonmetallic
8.37. Wire-reinforced
8.38. Dacron
8.39. Diameter
8.40. Flexibility
8.41. E.E.
8.42. Reinforced; pressure
8.43. Flexible
8.44. Expansion joint
8.45. Vibration dampener
8.46. Plain
8.47. Bends
8.48. Pressure
8.49. Plug
8.50. A long-radius elbow
8.51. Reducer
8.52. Gasket
8.53. Valves
8.54. Throttle; start; stop
8.55. Globe
8.56. Butterfly
8.57. Pressure; preset
8.58. Solid particles
8.59. Shut off
8.60. Lubricate
8.61. Water; condensate
8.62. Condensate
8.63. Absolute
8.64. Spring-loaded
8.65. Expands
8.66. Vacuum breaker

CHAPTER 9

9.1. Flow measurements are important because unit processes are designed for specific flow levels and process adjustments are based upon current levels of flow and are commonly controlled by flow rate adjustments.
9.2. 3 ft^3/sec
9.3. 2244 gal/min
9.4. 2.5 ft^3/sec
9.5. The Parshall flume is preferred. Weirs are not frequently used anymore because solids may collect behind the weir, causing odor and inaccurate flow measurements. Parshall flumes are now widely used for measuring wastewater flow, because they have no obstructions.

CHAPTER 10

10.1. Na
10.2. H_2SO_4
10.3. 7
10.4. Base
10.5. Changes
10.6. Solids; liquids; gases
10.7. Element
10.8. Compound
10.9. Periodic
10.10. Solvent; solute
10.11. An ion is an atom or group of atoms that carries a positive or negative electrical charge as a result of having lost or gained one or more electrons.
10.12. Colloid
10.13. Turbidity
10.14. True color is the result of dissolved chemicals.
10.15. Toxicity
10.16. Organic
10.17. 0; 14
10.18. Alkalinity is the water's ability to neutralize an acid.
10.19. Calcium; magnesium
10.20. Bases

CHAPTER 11

11.1. Bacteria, viruses, and protozoans
11.2. A river of good quality shows its highest bacterial numbers during rainstorms.
11.3 No
11.4. Bacteria reproduce by binary fission
11.5. Spheres, rods, and spirals
11.6. Typhoid, cholera, and gastroenteritis
11.7. Amoebic dysentery and giardiasis
11.8. Cyst
11.9. Host
11.10. Algae plug screens and machinery and also cause taste and odor problems
11.11. Freezing will not kill bacteria. Bacteria is Machiavellian; it is a survivor.

CHAPTER 12

12.1. Ecosystem
12.2. Benthos
12.3. Periphyton
12.4. Plankton
12.5. Free-swimming organisms belong to the pelagic group.
12.6. Neustons
12.7. Immigration
12.8. Autotrophs
12.9. Lotic
12.10. Dissolved oxygen solubility

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CHAPTER 13

13.1. Secondary maximum contaminant levels
13.2. Transpiration
13.3. Surface water
13.4. Agriculture, municipal wastewater plants, habitat and hydrologic modifications, resource extraction, and urban runoff and storm sewers
13.5. Solids content
13.6. Turbidity
13.7. Universal solvent
13.8. Alkalinity
13.9. Neutral state
13.10. Lead

CHAPTER 14

14.1. Muffle furnace, ceramic dishes, furnace tongs, and insulated gloves
14.2. 15 min
14.3. A grab sample is a sample collected all at one time. It is representative of the conditions only at the time taken.
14.4. It is necessary to use a grab sample for pH, DO, TRC, fecal coliform, and any test by NPDES permit for grab sample.
14.5. A composite sample is a series of samples collected over a specified period of time in proportion to flow.
14.6. Rules for sample collection include the following:
   a. Collect sample from a well mixed location
   b. Clearly mark sampling points.
   c. Have an easy location to read the sample.
   d. Make sure there are no large or unusual particles.
   e. Make sure there are no deposits, growths, or floating materials.
   f. Use corrosion-resistant containers.
   g. Follow safety procedures.
   h. Test samples as soon as possible.
14.7. The acceptable preservation method is to refrigerate at 4°C.
14.8. Absorption of water during cooling, contaminants, fingerprints, etc. can cause changes in weight during the testing procedure.

CHAPTER 15

15.1. Cone of depression
15.2. 12 in.
15.3. Concrete
15.4. Surface water, groundwater, GUDISW
15.5. GUDISW stands for groundwater under the direct influence of surface water
15.6. Two advantages of surface water sources are that they are (1) easily located, and (2) softer than groundwater.
15.7. Hydrology is the study of the properties of water and its distribution and behavior.
15.8. Zone of influence
15.9. GUDISW
15.10. The function of the bar screen at a surface water intake is to prevent large material from entering the intake.

CHAPTER 16

16.1. A watershed is a potential reserve area, usually distinct from the treatment plant, where natural or artificial lakes are used for water storage, natural sedimentation, and seasonal pretreatment with or without disinfection.
16.2. collection area into which water drains
16.3. "Keep it out" and "take it out" represent either of two choices in water utility management: keep it out of watershed or take it out during treatment
16.4. Algicide's purpose in reservoir management is to control algae and in turn decrease taste and odor problems
16.5. BMP means best management practices.

CHAPTER 17

17.1. Calcium and magnesium
17.2. Buffer
17.3. Sodium hydroxide
17.4. Chlorine Feed Rate (lb/d)

$$= \text{Dose (mg/L)} \times \text{Q (MGD)} \times 8.34$$
$$= 1.2 \text{ mg/L} \times 1.6 \text{ MGD} \times 8.34$$
$$= 1.2 \times 1.6 \times 8.34$$
$$= 16.0 \text{ lb/d}$$

17.5. 2.4 (60 ÷ 25)
17.6. Chlorine Dose (mg/L) – Chlorine Residual (mg/L)

$$= 1.0 \text{ mg/L} - 0.5 \text{ mg/L}$$
$$= 0.5 \text{ mg/L}$$

17.7. Residual = Dose – Demand

$$= 6.0 \text{ mg/L} - 3.3 \text{ mg/L}$$
$$= 2.7 \text{ mg/L}$$

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17.8. $$\text{Dose} = \frac{220 \text{ lb/d } Cl_2}{3.1 \text{ mg/L} \times 8.34} = \frac{220}{25.9} = 8.5 \text{ mg/L}$$

$$\text{Residual} = \text{Dose} - \text{Demand}$$
$$= 8.5 \text{ mg/L} - 6.9 \text{ mg/L}$$
$$= 1.6 \text{ mg/L}$$

17.9. A well log is best described as a description of the soil encountered during well construction, water quantity, well casing information, and well development and testing.

17.10. Dug well

17.11. Disinfection residual, turbidity, coliform analysis

17.12. National Sanitation Foundation (NSF)

17.13. Fit for human consumption

17.14. a. Determine the required chlorine feed rate:

$$\text{Feed Rate (lb/d)}$$
$$= \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34$$
$$= 0.6 \text{ mg/L} \times 1 \text{ MGD} \times 8.34$$
$$= 5.0 \text{ lb/d}$$

If we require 5 lb/d of chlorine, we will require more pounds of hypochlorite because it is not 100% chlorine. Remember that 68% of the hypochlorite is available chlorine (68% = 68/100 = 0.68).

b. Determine the pounds per day of hypochlorite required

$$Cl_2 \text{ Fraction} \times \text{Hypochlorite}$$
$$= \text{Available Chlorine}$$
$$0.68 \times x \text{ lb/day hypochlorite}$$
$$= 5 \text{ lb/d } Cl_2$$
$$x = \frac{5}{0.68}$$
$$= 7.36 \text{ lb/d}$$

17.15. Public

17.16. The hydrologic cycle describes the transport of the earth's water from one location to another.

17.17. Acute

17.18. Reduction of pathogens to safe levels

17.19. Hypochlorites

17.20. Effective disinfectants must reduce the number of pathogens to safe levels in water before the contact time is completed.

17.21. Feed Rate (lb/day)

$$= \text{Dose (mg/L)} \times \text{Q (MGD)} \times 8.34$$
$$= 0.4 \text{ mg/L} \times 5/3 \text{ MGD} \times 8.34$$
$$= 17.68 \text{ lb/d } Cl_2$$

17.22. $$\text{Residual} = \text{Dose} - \text{Demand}$$
$$= 10 \text{ mg/L} - 2.6 \text{ mg/L}$$
$$= 7.5 \text{ mg/L}$$

17.23. One possible interference of chlorine disinfection is that turbidity can entrap or shield microorganisms from the chlorine.

17.24 Feed Rate (lb/d)

$$= \text{Dose (mg/L)} \times \text{Q (MGD)} \times 8.34$$
$$= 0.8 \times 2.6 \times 8.34$$
$$= 17.35 \text{ lb/d}$$

17.25. Given the following:

Flow = 0.75 MGD
Shape = Circular
Size = radius = 20 ft
Depth = 10 ft

Find the detention time.

a. Find the tank volume.

$$v = \pi \times r^2 \times H$$
$$v = \pi \times (20 \text{ ft})^2 \times 10 \text{ ft}$$
$$v = 12{,}560 \text{ ft}^3$$

b. Find the flow rate.

$$Q = 0.75 \text{ MGD} \times 1{,}000{,}000$$
$$= 750{,}000 \text{ gal/d}$$

c. Find the detention time.

$$\text{Detention Time (h)}$$
$$= \frac{12{,}560 \text{ ft}^3 \times 7.48 \times 24 \text{ h/d}}{750{,}000 \text{ gal/d}}$$
$$= 3.0 \text{ h}$$

17.26. Feed Rate

$$= \text{Dose (mg/L)} \times \text{Flow (MGD)} \times 8.34$$
$$= 35 \text{ mg/L} \times 2 \text{ MGD} \times 8.34$$
$$= 70 \times 8.34$$
$$= 584 \text{ lb/d}$$

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17.27. Yes
17.28. Chlorine residual
17.29. The conditions are that (1) a link that connects two systems, and (2) a force that causes liquids in a system to move.
17.30. Moderate
17.31. Negative; low
17.32. Peristaltic metering pump
17.33. Purchase of buffer zone around a reservoir, inspection of construction sites, public education
17.34. Given the following:
Number of filters = 3
Size (each) = 10 × 7 ft
Operating: 1 out of service
Filtration Rate = 280 gal/min (this is the total capacity for both filters)
Find the filtration rate of filter (ft^2).
a. Find the total area of the filters.
Area of each filter = 10 ft × 7 ft = 70 ft^2
Total area of filters = 70 ft × 2 = 140 ft^2
b. Find the filtration rate.

$$\text{Filtration Rate} = \frac{280\ \text{gal/min}}{140\ \text{ft}^2}$$

$$= 2\ \text{gal/min/ft}^2$$

17.35. Given the following:
Filter area = 300 ft^2
Backwash rate = 15 gal/ft^2/min
Backwash time = 8 min
Find the amount of water for backwash (information on per foot of filter given, but want to find total water needed to backwash the entire filter).
a. Find total filtration rate.

$$15\ \text{gal} \times 300\ \text{ft}^2 = 4500\ \text{gal/min}$$

b. Find the amount of water in gallons required for each backwash (gallons per 8-min backwash time).

$$4500\ \text{gal/min} \times 8\ \text{min} = 36{,}000\ \text{gal}$$

17.36. $$\text{Velocity} = \frac{\text{Distance Traveled}}{\text{t}}$$

$$= \frac{600\ \text{ft}}{5\ \text{min}}$$

$$= 120\ \text{ft/min}$$

17.37. Material Safety Data Sheets (MSDS)
17.38. Chlorination and filtration
17.39. Pump more than rated capacity
17.40. Hypochlorous acid
17.41. Protozoa
17.42. The removal or inactivation of the most resistant pathogens
17.43. Corrosivity
17.44. Turbidity, paddles speed, pH
17.45. In this problem, we want to find the velocity. Therefore, we must rearrange the general formula (V = Q/A) to solve for velocity. Given the following:
Q = 11.2 ft^3/sec
A = 2.5 × 14 ft
Find the average velocity.
a. Find the area.

$$A = W \times A$$

$$= 2.5\ \text{ft} \times 1.4\ \text{ft}$$

$$= 3.5\ \text{ft}^2$$

b. Find the average velocity.

$$V = \frac{Q}{A}$$

$$= \frac{11.2\ \text{ft}^3/\text{sec}}{3.5\ \text{ft}^2}$$

$$= 3.2\ \text{ft/sec}$$

17.46. Given the following:
H = 100 ft
Diameter = 20 ft
Cylindrical shape
Find the total gallons of water contained in the tank.
a. Find the volume in cubic feet.

$$v = 0.785 \times (\text{Diameter})^2 \times H$$

$$= 0.785 \times (20\ \text{ft})^2 \times 100\ \text{ft}$$

$$= 0.785 \times 400\ \text{ft}^2 \times 100\ \text{ft}$$

$$= 31{,}400\ \text{ft}^3$$

b. Find the amount of <u>gallons</u> of water it will contain?

$$31{,}400\ \text{ft}^3 \times 7.48\ \text{gal/ft}^3 = 234{,}872\ \text{gal}$$

17.47. Rapid mix, flocculation, sedimentation
17.48. The removal of color, suspended matter, and organics
17.49. The goal of chemical precipitation is to transform soluble ions to insoluble compounds.
17.50. Add 3 to 4 times the theoretical amount.
17.51. 5%

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17.52. Given the following:

Distance = 1500 ft

t = 4 min

Find the velocity in feet per minute and feet per second.

a. Find the velocity in feet per minute.

$$V = \frac{1500 \text{ ft}}{4 \text{ min}}$$

$$= 375 \text{ ft/min}$$

b. Convert minutes to seconds

$$375 \text{ ft/min} \times 1 \text{ min/60 sec} = 6.25 \text{ ft/sec}$$

17.53. Gate

17.54. A treatment facility must achieve optimum corrosion control.

17.55. 50%

17.56. Sodium fluoride (NaF)

17.57. Mottled teeth enamel

17.58. 0.90 – 0.15 = 0.75 mg/L

17.59. Amount of chlorine to add for breakpoint chlorination; correct amount of coagulant to use for proper coagulation; length of flash mix; proper amount of mixing and settling time.

17.60. Corrosion control technology

17.61. Given the following:

Q = 350 GPM

Pipe Size = 6 in.

Find the average velocity.

a. Convert gallons to cubic feet.

$$\frac{350 \text{ gal/min}}{7.48 \text{ gal/ft}^3} = 46.8 \text{ ft}^3\text{/min}$$

b. Find the cross-sectional area of the pipe.

$$A = \pi \times r^2$$

$$= 3.14 \times 3 \text{ in.} \times 3 \text{ in.}$$

$$= 28.26 \text{ in.}^2$$

c. Convert square inches to square feet.

$$\frac{28.26 \text{ in.}^2}{144 \text{ in.}^2/\text{ft}^2} = 0.20 \text{ ft}^2$$

d. Find velocity in feet per minute.

$$V = \frac{46.8 \text{ ft}^3\text{/min}}{0.20 \text{ ft}^2} = 234 \text{ ft/min}$$

e. Convert minutes to seconds.

$$234 \text{ ft/min} \times 1 \text{ min/60 sec} = 3.9 \text{ ft/sec}$$

17.62. Air, chlorine, or potassium permanganate

17.63. pH, alkalinity, hardness

17.64. Adsorption

17.65. An additional source of alkalinity is most effective when added prior to the rapid mix basin.

17.66. Supplemental backwash air flow and surface sweeps should be turned off before the backwash, when water reaches the lip of the wash water trough.

17.67. Chlorine

17.68. True

17.69. True

17.70. Aeration, boiling, adsorption

17.71. Vol = (3.14) (15 ft^2) × 15′ × 7.48 gal/ft^3 = 79,269 gal

17.72. Powdered activated carbon

17.73. Iron and manganese

17.74. Copper

17.75. Soluble polyvalent cations

17.76. The iron atom gains an electron in going from the +2 oxidation state to the +3 form.

17.77. Bicarbonate

17.78. Negative head

17.79. Gravity

17.80. Influent

17.81. Uniform

17.82. Maximize the conversion of organic carbon from the dissolved phase to the particulate phase; the removal of natural organic material; optimize the removal of DHP precursor material.

17.83. 30 h

17.84. Phenyl arsine oxide

17.85. Given the following:

Surface area of pond = 20 acres

Height of water collected = 2 in.

Find the number of gallons collected in the reservoir after the storm.

a. Convert acres to square feet.

$$20 \text{ acres} \times 43{,}560 \text{ ft}^2\text{/acre} = 871{,}200 \text{ ft}^2$$

b. Convert inches to feet.

$$2 \text{ in.} \times \text{ft/12 in.} = 0.167 \text{ ft}$$

c. Find the volume of water collected.

$$v = A \times H$$

$$= 871{,}200 \text{ ft}^2 \times 0.167 \text{ ft}$$

$$= 145{,}490 \text{ ft}^3$$

d. Convert cubic feet to gallons.

$$145{,}590 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 1{,}089{,}013 \text{ gal}$$

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17.86. 20.0 lb/d Cl_2

17.87. $70 \text{ ft} \times 0.4 = 28 \text{ ft}$

$28 \text{ ft} \times 0.433 = 12.1 \text{ psi}$

17.88. Groundwater
17.89. Aeration, boiling, adsorption
17.90. Addition of powdered activated carbon
17.91. Permeability
17.92. Water table
17.93. Waterborne
17.94. Coagulant
17.95. Greater
17.96. Copper sulfate
17.97. Lime
17.98. Disinfected
17.99. Oxygen
17.100. Binary fission

CHAPTER 18

18.1. Both the licensed operator and the responsible official must sign the DMR.
18.2. The COD test measures the amount of organic material in a sample that can be oxidized by a strong oxidizing agent.
18.3. Prevent disease, protect aquatic organisms, protect water quality
18.4. Dissolved and suspended
18.5. Organic indicates matter that is made up mainly of carbon, hydrogen, and oxygen and will decompose into mainly carbon dioxide and water at 550°C. Inorganic matter consists of mineral materials, such as salt, ferric chloride, iron, sand, gravel, etc.
18.6. Algae, bacteria, protozoa, rotifers, virus
18.7. Carbon dioxide, water, more organics, stable solids
18.8. Toxic matter, inorganic dissolved solids, pathogenic organisms
18.9. Raw effluent
18.10. Disease-causing bacteria originate from body wastes of humans who have diseases.
18.11. Disease-causing
18.12. Domestic waste
18.13. Industrial waste
18.14. 4.4%
18.15. 2.3 ft
18.16. 43,785 lb (5,250 gal × 8.34 lb/gal)
18.17. 14,362 gal
18.18. 850.7 lb/d
18.19. 686 kg/d
18.20. 0.121 MGD
18.21. 8477 people/d
18.22. 9.41 lb/gal
18.23. To ensure proper operation, cutters may be sharpened or replaced when needed. Cutter alignment must be adjusted as needed.
18.24. Grit is heavy inorganic matter. Examples include sand, gravel, metal filings, egg shells, coffee grounds, etc.
18.25. 0.7 ft/sec
18.26. This indicates that there is a large amount of organic matter in the gut. The aeration rate must be increased to prevent settling of the organic solids.
18.27. The purpose of primary treatment is to remove settleable and flotable solids.
18.28. The purpose of the settling tank is to remove the settleable solids formed by the biological activity.

18.29. $$\frac{0.785 \times 90 \text{ ft} \times 90 \text{ ft} \times 12 \text{ ft} \times 7.48 \text{ gal/cu ft} \times 24 \text{ hr/day}}{2.25 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}$$

$$= 6 \text{ hrs}$$

$$\frac{2.25 \text{ MGD} \times 1{,}000{,}000}{0.785 \times 90 \text{ ft} \times 90 \text{ ft}}$$

$$= 354 \text{ gpd/sq ft}$$

$$\frac{2.25 \text{ MGD} \times 1{,}000{,}000 \text{ gal/MG}}{3.14 \times 90 \text{ ft}}$$

$$= 7951 \text{ gpd/ft}$$

18.30. Stabilization pond, oxidation pond, polishing pond.
18.31. Settling, anaerobic digestion of settled solids, aerobic or anaerobic decomposition of dissolved and colloidal organic solids by bacteria that produces stable solids and carbon dioxide, photosynthesis.
18.32. Summer effluent is high in solids (algae) and low in BOD; winter effluent is low in solids and high in BOD.
18.33. Using mechanical or diffused aeration equipment eliminates wide diurnal and seasonal variation in pond DO.
18.34. Standard, high rate, and roughing
18.35. Increase waste rate
18.36. Decrease; decrease; decrease; increase; increase
18.37. 10 containers
18.38. 88 d
18.39. $2,823.49 (103 cylinders)
18.40. 4,716 lb/d
18.41. 21.5 lb
18.42. 27 d
18.43. 64.1%
18.44. National pollutant discharge elimination system

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18.45. A primary sludge can be freshened by increasing the primary sludge pumping rate or by adding dilution water.
18.46. 7
18.47. The seeded BOD test is required either because the microorganisms have been killed or are absent.
18.48. The time to do the test (3 h vs. 5 d)
18.49. Dark greasy
18.50. The activity of the bacteria increases.
18.51. Temperature, pH, toxicity, waste rate, aeration tank configuration
18.52. Facultative organisms can function with or without DO. DO is preferred, but chemically combined oxygen, such as sulfate or nitrate, can be used.
18.53. Organic
18.54. Living organisms
18.55. Final
18.56. Colloidal
18.57. Not possible
18.58. Aerobic; facultative
18.59. Different
18.60. Reduced
18.61. Temperature
18.62. BOD
18.63. F:M
18.64. Secondary clarifier weirs
18.65. The purposed of the secondary clarifier is to separate and return biosolids to the aeration tank.
18.66. Declining
18.67. 1.5; 2.5
18.68. The operator would increase MLVSS concentration.
18.69. Decreased waste rate
18.70. Decreased MCRT
18.71. The Gould sludge age assume the source of the MLVSS in the aeration tank is the concentration of aeration influent solids.
18.72. Complete mix is more resistant to shock loads.
18.73. Decrease the grit channel aeration rate.
18.74. Increase
18.75. Floor level
18.76. $22.77
18.77. Anoxic
18.78. C:N:P
18.79. Secondary
18.80. False
18.81. 2 ft/sec
18.82. The pH of wastewater would be lowered.
18.83. Chlorine residual
18.84. 2 h
18.85. 0.1
18.86. 800 gal/d/ft^2
18.87. Monochloramine
18.88. 0.2; 0.5
18.89. Nitrogen
18.90. Decrease explosive hazard, decrease odor release, maintain temperature, and collect gas
18.91. Algae
18.92. Dissolved solids
18.93. 0.0005 ppm

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Appendix B

Formulae

1. Area
   a. Rectangular Tank

$$A = L \times W$$

   b. Circular Tank

$$A = \pi \times r^2 \text{ or } A = 0.785 \times \text{Diameter}^2$$

2. Volume
   a. Rectangular Tank

$$v = L \times W \times D$$

   b. Circular Tank

$$v = \pi \times r^2 \times H \text{ or } 0.785 \times \text{Diameter}^2 \times H$$

3. Flow:

$$\text{Gal/d} = \text{gal/min (gpm)} \times 1440 \text{ min/d}$$

$$\text{Gal/d} = \text{gal/h} \times 24 \text{ hr/d}$$

$$\text{MGD} = \frac{\text{gal/d}}{1{,}000{,}000}$$

4. Dose:

$$\text{lb} = \text{ppm} \times \text{MG} \times 8.34 \text{ lb/gal}$$

$$\text{ppm} = \frac{\text{lb}}{\text{MG} \times 8.34 \text{ lb/gal}}$$

5. Efficiency (% removal)

$$\text{Efficiency (\% removal)} = \frac{\text{Influent} - \text{Effluent}}{\text{Influent}} \times 100$$

6. Weir loading

$$\text{Weir Loading (overflow rate)} = \frac{\text{Total gal/d}}{\text{Length of Weir}}$$

7. Surface settling rate

$$\text{Surface Settling Rate} = \frac{\text{Total Gallons/d}}{\text{Surface Area of Tank}}$$

8. Detention time

$$\text{DT (h)} = \frac{\text{Capacity of Tank (gal)} \times 24 \text{ h/d}}{\text{Flow Rate (gal/d)}} \times 100$$

9. Horsepower

$$\text{Horsepower (hp)} = \frac{\text{gal/min} \times \text{Head (ft)}}{3960 \times \text{Total Efficiency}}$$

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